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ASSESSING THE IMPACT OF COMMUNICATION NETWORKS ON RELIABLE COORDINATION AND ANCILLARY SERVICES FROM RENEWABLE GENERATION PLANTS

BY
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Assessing the Impact of Communication Networks on Reliable Coordination and Ancillary Services from Renewable Generation Plants

Ph.D. Dissertation

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Abstract

Wind power (WP) and photovoltaic (PV) power plants are expected to jointly produce a large share of renewable energy generation capacity needed to reach the target of having green energy around the globe. For instance, the Danish government aims to achieve a power production of 50% from such renewable energy sources by the end of 2020, while a 100% by 2050. These energy resources are categorized as having volatile power production, which in turn imposes the requirement that the bulk addition of large-scale renewable generation (ReGen) plants to a power grid should not be detrimental to the overall stability of the power system. This requirement can be ensured by requiring WP and PV plants to have similar regulating properties as conventional power plants along with coordinating their grid support services. The ReGen plants will therefore have to play a role not only into the energy production, but also into the delivery of system services (also known as ancillary services) that are necessary to ensure the system stability, including both transmission and distribution level. This fact leads to fundamental changes in the way transmission and distribution network operators will have to use grid support services from ReGen plants to manage the voltage and frequency stability in the future power system, which will continuously evolve through new interconnections and use large scale renewable technologies.

Among other requirements, investigation on strengthening system reliability are necessary regarding faster and reliable communication (i.e. between WP/PV farms and system operators control rooms), dedicated tuning of the control strategies, estimation of available power etc. are crucial step stones towards a future resilient power system. The ability to provide faster and reliable communication in such a scenario will highly depend on an underlying communication infrastructure that allows exchange of information between different grid assets and controllers. Generally, this component in networked control systems (such as the smart grids) is in fact highly critical for operations to be executed as planned. If the communication network does not perform as expected, it may in turn have serious consequences on the power system being controlled over these networks. In smart grids, changing

communication properties (such as delays and packet losses) or other disruptions in communication can lead to serious control performance degradation. In worst case, such performance degradations may even manifest themselves as blackouts, over-voltages and other physical damages in the power grid. Therefore, it is essential to not only assess the impact of communication networks and data access procedures in the provision of each grid support service but also understand numerically the implications of network faults/cyberattacks on these services.

This thesis investigates two different grid support services: **a)** frequency control and **b)** voltage control coordination from renewable generation plants in distribution grids, which are assessed for data exchange scheduling based on communication networks. The two services are selected since they cover different timing requirements in terms of control loop duration, from less than a second to minutes, respectively. To investigate delay, reliability and other communication requirements for the provision of the two selected services and control coordination from ReGen plants, several evaluation frameworks have been developed. These frameworks range from analytical and simulation frameworks to Hardware-in-the-loop test setups. Further, an information quality metric named 'mismatch probability' is used as a performance metric that links communication network performance to the overall system performance. Mismatch probability calculates the probability of having incorrect information at the time of control actuation due to communication network delay or message loss. The advantage of using mismatch probability is that is combines in a scalar value the impact of information access methods along with network delays, and put those in relation to the dynamics of the grid scenario.

By considering the communication network to be an active resource offering the provisioning of quality of service as well as network reconfiguration, mismatch probability has been investigated to be used as additional measures for improving control performance in case of higher transport layer delays and higher message loss rates. Moreover, this metric is linked to the provision of ancillary services from renewable generation plants and is used to find out a trade-off between different quality-of-service parameters with the possibility to enhance communication reliability. The overall assessment done in this dissertation provides insights for the smart grid stakeholders regarding the importance and characteristics of Information and Communication Technologies (ICT) related issues that must be considered effectively during the design and assessment of any ancillary service from ReGen plants in future power systems. Additionally, this dissertation contributes to provide directions for improvement/optimization of IEC based standards that define requirements for communication between electrical substations and control centers.

Resumé

Det forventes at vind- og solkraft tilsammen vil generere en stor andel af den kapacitet af vedvarende energi, som er nødvendig for at nå målet om at have grøn energi i verden. For eksempel har den danske regering som mål at opnå 50% af elproduktionen fra vedvarende energi før udgangen af 2020, og 100% ved udgangen af 2050. Da vind- og solkraft er afhængig af vejret, er disse strømkilder ustabile. Så når store mængder af sol- og vindkraft tilsluttes til elnettet, er det et krav at disse ikke må have en skadelig effekt på den overordnede stabilitet af elnettet. Dette krav kan opfyldes ved at kræve, at disse strømkilder har samme reguleringsmuligheder som traditionelle kraftværker, samt ved at koordinere deres støtteservices. Vedvarende energi er derfor nødt til at spille en rolle i energiproduktionen, men også i at levere de nødvendige services for at sikre stabiliteten af systemet på både transmissions- og distributionsniveau. Dette faktum leder til grundlæggende ændringer i måden, hvorpå transmissions- og distributionsnetværksoperatører bruger støtteservices fra producenter af vedvarende energi for at styre stabiliteten af spænding og frekvens i fremtidens elnet, hvilket vil udvikle sig kontinuert via nye forbindelser og ved brugen af vedvarende energi teknologier i store mængder.

For at opnå et fremtidigt fleksibelt energisystem kan følgende tiltag fremhæves; undersøgelse af hvordan systemstabiliteten forstærkes vha. hurtigere og mere pålidelig kommunikation, (f.eks. imellem vindmølle og solcelle parker og kontrolrum), dedikeret indstilling af kontrolstrategier og estimering af tilgængelig strøm. At være i stand til at tilbyde hurtigere og mere pålidelig kommunikation i et sådan scenarie vil afhænge meget af den underliggende kommunikationsinfrastruktur, som tillader udveksling af information mellem de forskellige elnets ressourcer og controllere. I distribuerede kontrolsystemer generelt er dette en kritisk komponent, som sikrer, at funktioner kan udføres som planlagt. Hvis kommunikationsnetværket ikke yder som forventet, kan det have seriøse konsekvenser for el-systemet, som styres via dette netværk. I forbindelse med smart grid kan skiftende egenskaber af kommunikationsnetværk, (f.eks. svartider og pakketab), og andre forstyrrelser have stor indflydelse på degradering af kontrolydelsen. I værste tilfælde kan så-

danne udsving i ydelse forårsage strømsvigt, overspænding og andre fysiske skader på elnettet. Derfor er det essentielt ikke kun at evaluere påvirkningen af kommunikationsnetværk og procedurer for tilgang af data for smart grid støtteservices, men også at forstå de numeriske konsekvenser af netværksfejl eller angreb på disse services.

Denne afhandling undersøger to forskellige støtteservices af smart grid; **a)** frekvenskontrol og **b)** spændingskontrol-koordinering fra producenter af vedvarende energi i distributionsnetværk, som er evalueret på baggrund af skedulering af udveksling af data over kommunikationsnetværk. Disse to services er valgt, da de dækker over forskellige tidskrav i forhold til varigheden af kontrol-kredsløbet fra mindre end et sekund til flere minutter. For at undersøge svartider, pålidelighed og andre krav til kommunikationen til de to valgte services og til kontrolkoordinationen fra vedvarende energi producenter, er der udviklet flere forskellige evalueringssystemer. Disse systemer strækker sig fra analytisk og simuleringsbaseret til hardware-in-the-loop testopstillinger. Ydermere er der brugt en kvalitetsmetrik, kaldet "mismatch probability", som forbinder svartider i kommunikationsnetværk med den overordnede systemydelse. "Mismatch probability" udregner sandsynligheden for ikke at have den korrekte information, når den bruges i forbindelse med kontrol, som konsekvens af svingende svartider eller pakketab. Fordelen ved at bruge "mismatch probability" er, at man kombinerer indflydelsen af metoden for, hvordan informationer er tilgået med indflydelsen af svartider i en enkelt værdi, samt sætter disse indflydelser i relation til dynamikkerne af smart grid scenariet.

Ved at betragte kommunikationsnetværk som en aktiv ressource, der leverer kvalitetsmæssig service og netværkskonfiguration, er det undersøgt, hvordan "mismatch probability" kan blive brugt til at forbedre kontrolydelsen i forbindelse med netværksforsinkelser på højere netværkslag samt forhøjede pakketabsrater. Desuden er denne metrik forbundet til leveringen af støtteservices fra produktionen af vedvarende energi, og den er brugt til at finde en afvejning mellem forskellige kvalitetsmæssige serviceparametre med muligheden for at forbedre pålideligheden af kommunikationen. Den overordnede evaluering, som er udført i denne afhandling, giver interessenter af smart grids indsigt i vigtigheden og karakteristika af informations- og kommunikationsteknologier (ICT) og deres relaterede udfordringer. Disse udfordringer skal tages i betragtning i forbindelse med design og evaluering af alle støtteservices fra produktionen af vedvarende energi i fremtidens el-systemer. Denne afhandling giver også retningslinjer til at forbedre eller optimere IEC baserede standarder, som definerer krav til kommunikationen mellem el-netværkets understationer og kontrolcentre.

Contents

Thesis Details

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[C] Kamal Shahid, Lennart Petersen, Rasmus Løvenstein Olsen, and Florin Iov, "ICT Based HIL Validation of Voltage Control Coordination in Smart Grids Scenarios." *Energies* 2018. Available: http://www.mdpi.com/1996-1073/11/6/1327

[D] Kamal Shahid, Mufit Altin, Lars M. Mikkelsen, Rasmus Løvenstein Olsen, and Florin Iov, "ICT based Performance Evaluation of Primary Frequency Control Support and Coordination from ReGen Plants in Smart Grids." *Energies* 2018. Available: http://www.mdpi.com/1996-1073/11/6/1329

[E] Kamal Shahid, Aamir Saeed, Thomas le Fevre Kristensen, and Rasmus Løvenstein Olsen, "Impact of Transport Layer Protocols on Reliable Information Access in Smart Grids." *IEEE International Conference on Innovative Smart Grid Technologies (IEEE ISGT Europe 2017)*, 2017, Politecnico di Torino in Torino, Italy. [Online]. Available: http://ieeexplore.ieee.org/document/8260250/

[F] Kamal Shahid, Lennart Petersen, Rasmus Løvenstein Olsen, and Florin Iov, "ICT Requirements and Challenges for Provision of Grid Services from Renewable Generation Plants." *2018 International Conference on Smart Grid and Clean Energy Technologies (ICSGCE 2018)*, 2018, Kuala Lumpur, Malaysia.

[G] Rafia Umair, Kamal Shahid and Rasmus Løvenstein Olsen, "Information Reliability in Smart Grid Scenario over Imperfect Communication Networks using IEC-61850 MMS" 17^{th} *International Conference on Smart Technologies (IEEE EUROCON 2017)*, 2017, Ohrid, Macedonia. [Online]. Available: http://ieeexplore.ieee.org/document/8011079/

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During this PhD I have worked on a national level project named RePlan (Ancillary Services from Renewable Power Plants). This project provided me with lots of experiences from which I learned a lot and got the opportunity to work with professionals from various fields.

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Kamal Shahid
Aalborg University, July 2, 2018

Part I

Introduction

Chapter 1

Introduction

This chapter will introduce the content and problem area of this dissertation by giving an overview of the background. This will serve as a motivation for working with the broad area of Smart Grids. Then the specific problem area will be outlined followed by a problem statement.

1.1 Background & Motivation for Smart Grids

In the 1880s, people started opting for improved lighting source (the electricity) after getting tired of using the gas lamps. Soon after the invention of the electric light bulb, its popularity rose rapidly, and electricity utility companies promptly leveraged the "economies of scale", that led to the foundation of a centralized system of power generation, distribution, and overall management [6]. The production of electricity at large central power plants typically located in remote areas meant 'a large-scale generation of electricity at a smaller number of facilities'. In the centralized power production system, electricity is transported to the long distant regional and neighborhood substations via high-voltage transmission lines. The transportation of electricity over long distances was achieved based on the AC approach, also known as High Voltage Alternating Current (HVAC), and remained the backbone of the power transmission system for over a hundred years [22]. (Note: long distance electricity transmission via DC approach, also known as High Voltage Direct Current (HVDC) is getting more popular [22], for reasons out of scope of this dissertation). After stepping down the voltage to a level that could be fed into a local distribution grid, it is finally delivered for use in homes, offices etc. This electric power system expanded from the small cluster of customers to a nationwide 'system of systems' that started delivering electricity to towns and cities throughout a country [2]. As electricity became more and more indispensable, regional systems took up the responsibility to coordinate electricity generation and ensure reliable system operation. For more than a century, the structure of electrical-energy network remained fundamentally the same, revolving around a centralized system of electricity generation and distribution [6].

The original design of the electricity-grid based on centralized power generation was novel and a great achievement by that time. Centralized power plants such as large fossil-fired gas, coal as well as nuclear boilers (to drive turbine generators via steam) and even large hydro power plants were the main source to provide bulk power. However, as societies continued to develop, not only the demand for electricity increased but also the nature and timing of electricity consumption changed. With these continuous developments, centralized power generation plants became prone to unreliability and instability under unpredictable events, and even often susceptible to attacks [17]. This led the power delivery infrastructures to suffer in terms of inefficiencies in power balancing, outdated engineering, aging equipment as well as environmental related concerns etc. The inefficiencies in the electricity grid and other several problems were addressed by introducing the concept of distributed generation (DG) i.e. utilizing smaller power generation plants to power homes, businesses and communities. In [10], DG is described as: "the use of small-scale power generation technologies located close to the load being served, capable of lowering costs, improving reliability, reducing emissions and expanding energy options". DG took advantage of replacing fewer conventional large-scale power plants to several different-scale (large, medium, small) renewable energy sources (RES) such as wind, solar, and hydropower. However, the power grids were mainly designed for a downward power flow (as in centralized generation) and not for the distributed nature of power production where the power flows both upwards as well as downwards (i.e. active/reactive power) in unpredictable ways. Moreover, connecting DG plants to the grid via power converters injected harmonics into the power system. The connection of such distributed energy sources also affects the system voltage (such as causing rise/drop/fluctuations in voltage levels) if utility supply is not properly coordinated [23]. Based on the network configuration, the level of penetration as well as the nature of the technology used for DG, the power injection from DG may increase the power losses in distribution system [23]. Thus, the addition of DG led to a greater unpredictability of the power consumption and thereby several problems for the power utility companies as well as the power grid.

According to the U.S Government's International Energy Outlook 2008 [7], energy consumption around the globe is anticipated to increase by 50% from 2005 to 2030. Moreover, there are countries such as Denmark that have set goals to make the country independent of fossil fuel by 2050 [13]. A key element in achieving this goal is energy efficiency along with an increased use of renewable energy mainly from wind and solar photovoltaic power plants [13, 18, 20, 21]. To cope with the huge increase in the energy consumption and respond to the rising challenges/opportunities faced by the future power grid in terms of huge penetration of renewable energy, the notion of "redesigning" the power grid was presented. The concept of "redesigned future power grid" was developed in 2006 by the European Technology platform [11] and termed it as "Smart Grid" (SG). As the name implies, SG will be an electricity network that could smartly (or intelligently) integrate the activities of all connected users – generators and consumers – in order to efficiently deliver sustainable, economical and secure supply of electricity [16]. In a report prepared by Litos Strategic Communication for the U.S. Department of Energy [10], SG is defined as: "*An automated, widely distributed energy delivery network, the Smart Grid will be characterized by a two-way flow of electricity and information and will be capable of monitoring everything from power plants to customer preferences to individual appliances. It incorporates into the grid the benefits of distributed computing and communications to deliver real-time information and enable the near-instantaneous balance of supply and demand at the device level*". While, as per the European Technology platform [11], "*the deployment of SGs must not only include market and commercial considerations, environmental impact, regulatory framework, standardization usage, Information and Communication Technology (ICT) and migration strategy but also societal requirements and governmental edicts*". This would mean an electrical power system with huge capability of technical, informational as well as organizational interoperability [11].

With several benefits foreseen with the development of SG, reference [10] highlights an important aspect i.e. SG will be "fully accommodating renewable and traditional energy sources". The following section briefly presents the aspects and challenges associated to the anticipated huge penetration of RES to the existing power gird. The presented explanation will lead to understand research questions raised and addressed in this dissertation.

1.2 Smart Grid Scenario with huge penetration of RES

Climate change is one of the biggest environmental challenges that the planet "earth" has ever faced. The main cause behind this emerging challenge is our high dependence on fossil fuels i.e. burning coal, petroleum and other fossil fuels has remained the primary means of producing electricity for decades. This has also led the world to heavy concentration of pollutants in the air as well as water. In addition to the environmental challenges, our high dependence on limited natural resources has led to rely more and more on the world's supply of fossil fuels. Higher the demand of electricity with developing societies, higher the demand for fossil fuels. Ultimately, the cost associated to the fuels based on natural resources keeps on increasing, which is reflected in terms of large electricity bills.

This led the world leaders and environmental experts to think of exploring and relying more and more on renewable sources of energy. These energy sources mainly include solar energy, wind energy and hydropower which never runout, unlike fossil fuels. The RESs are also expected to help in significantly reducing the amount of carbon emission from this planet. For this, several hundred international environmental agreements exist that link different number of countries [3]. Further, since the RES are mainly based on the unlimited and free natural resources (i.e. sun, wind, water), by relying more and more on these sources of energy, reduced energy bills could also be achieved. Due to these and many such reasons, investments in RES (including hydropower) have approximately doubled compared to the investment in fossil fuel based power generation, reaching USD 249.8 Billion [24]. Countries such as USA and China are heavily investing in producing energy from wind and solar power plants along with hydro and biofuels [24]. At national level, around thirty countries currently (to-date) have RES contributing over 20% of the total energy supply. While Norway and Iceland generate maximum of their electricity using renewable energy, relying predominantly on hydropower and geothermal energy, respectively. Similarly, the government of Denmark has set goals to get an entirely renewable energy based power grid system by the year 2050 [13]. Specifically in Denmark, this goal will be accomplished with a large share of wind energy [18].

Despite the fact that RES (especially wind and solar energy) have numerous environmental and economic benefits, there are many challenges to be addressed with huge penetration of such energy sources. For instances, wind and solar power plants entirely depend on wind and sun, respectively, to produce energy. This dependency on weather conditions poses mainly two challenges in the power production from such sources i.e. variability and uncertainty (also summarized as "intermittency") [15]. To ensure stability of the power grid in such a situation, two of the possibilities proposed in [15] are:**1)** to shift the consumption of energy to other available sources of energy or **2)** having energy reserves ready so that energy can be produced when there is not enough available due to unfavorable weather conditions. Here, the former being feasible is mainly used in scenarios of "peak shaving", while the latter can rather be highly expensive [15]. (Note: here, peak shaving refers to a technique used to reduce electrical power consumption during periods of maximum demand on the power utility [1]). Secondly, conventional power generators are typically synchronous generators that contribute to the system inertia to maintain constant grid frequency (for details, see Section 3.2). However, RES like WPP and PVP are characterized to be non-synchronous energy generators. Thus, replacing a substantial portion of large conventional synchronous generators by RES will cause reduced power system inertia, which in turn will result in a much higher rate of change of frequency during system disturbances [14]. Furthermore, another challenge associated with the use of RES is that these give rise to a more distributed power generation concept (see Section 1.1). While, as shown in Figure 1.1, the increasing penetration of RES into the distribution systems may also reverse the power flow dependent on the present amount of generation and consumption leading to rising voltage levels [15]. As aforementioned, the current power grids are not designed to handle this situation. Therefore, the foreseen high penetration of wind as well as solar power into the electricity supply necessitates that this bulk addition of large-scale renewable generation is not detrimental to the overall stability of the power system.

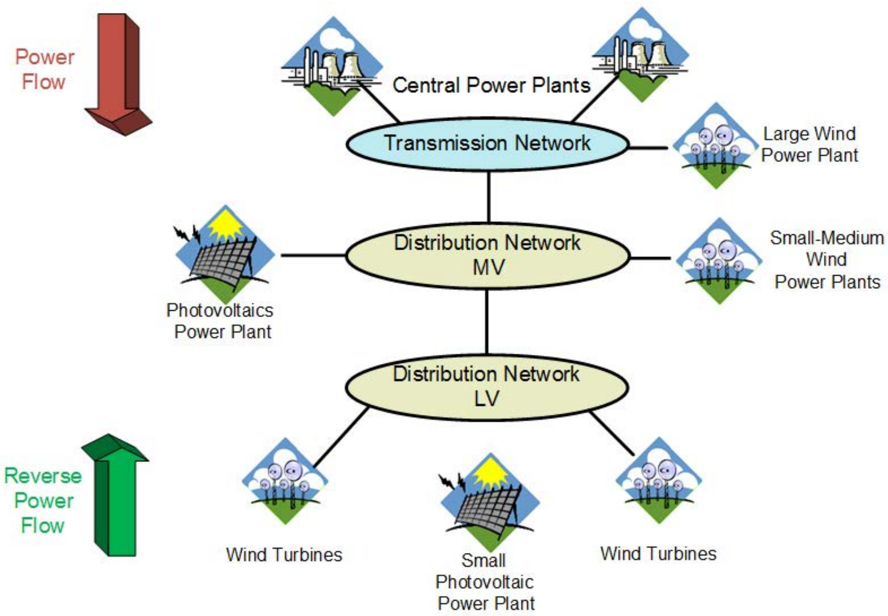

Fig. 1.1: Reverse power flow due to huge penetration of RES

1.3 Ancillary Serivces from Renewable Power Plants

Even though there are several ways to ensure that the bulk addition of RES into the power system will not be detrimental to the stability of a power system (see [18, 20, 21]), this thesis investigates the method proposed by RePlan (Ancillary Services from Renewable Generation Plants) project. According to RePlan, one way is to require wind power (WP) and photovoltaic (PV) power plants to have similar regulating properties as conventional power plants as well as to coordinate their grid support services. With the proposed solution, the renewable generation (ReGen) plants will thus have two roles to play in future:

1. Power production (as it is today),
2. Delivery of grid support services (namely ancillary services (AS)) which are required to ensure the system stability - comprising both transmission as well as distribution level [18].

There are different definitions proposed for the term 'ancillary services' that too depends on the context in which it is being used. One possible definition/description for ancillary services given in [9] is as:
"*Ancillary services are all grid support services required by the transmission or distribution system operator to maintain the integrity and stability of the transmission or distribution system as well as the power quality. These needs can be fulfilled by connected generators, controllable loads and/or network devices.*"

These ancillary services are grouped into the following three main groups of services (for details, see [9, 19]):

1.3.1 Voltage Control

This service is required to maintain the power system voltage within the prescribed bounds, not only during the course of normal operation but also during disturbances by keeping the balance of generation and consumption of reactive power [9]. Voltage control can be accomplished via reactive power control, power factor control or even by a combination of these two [9]. For this reason, it is often (generally and in dissertation) referred to as voltage/reactive power control.

1.3.2 Frequency Control

These services are related to the short-term balance of energy and frequency of the power system [9]. It includes primary/secondary (automatic) as well as tertiary (manual) frequency regulation and operational reserves. The frequency control has several time scales of operation that differ in their response times in different systems [9]. The European Network of Transmission System Operators (ENTSO-E) [12] classifies frequency control into the following types:

1. Frequency Containment Reserve (FCR) or Primary Frequency Control
2. Frequency Restoration Reserve (FRR) or Secondary Frequency Control
3. Replacement Reserve (RR) or Tertiary Frequency Control

1.3.3 System Restoration

In case of a blackout, these services are required to bring back the electrical power system to normal operation.

For the details of each of the ancillary service (as well as their types), the readers are urged to go through [9, 19]. Additionally, two reliability indicators (which are out of the scope of this dissertation) are also worth to explore in context of system restoration services, i.e. **a)** SAIFI (System Average Interruption Frequency Index) which is the average number of interruptions that a customer would experience [5], and **b)** SAIDI (System Average Interruption Duration Index) which is the average outage duration for each customer served [4]. However, in this dissertation following two ancillary services have been considered:

1. Voltage/Reactive Power Stability Support

2. Frequency/Active Power Stability Support

1.4 Smart Grid Multi-Layer Architecture Model

The CEN-CENELEC-ETSI Smart Grid Coordination Group [8] abstracts the SG architecture model into different interoperability layers, domains and zones, as shown in Figure 1.2. The purpose of this framework is to allow a clear presentation and simple handling of the complex SG architecture model. Each entity in the framework has a specific role to play to ensure smooth and reliable power supply in future. At the component layer level, smart controllers would be required both among the entities in the power grid as well as those that regulate these entities at the system operator level. These controllers will be designed such that they not only access and acquire the necessary information as per requirement, but also send control signals in response. This would mean a two-way communication between the controllers in a power grid, which will be achieved via the underlying communication networks and governed by the protocols defined in the 'communication layer' of Figure 1.2.

It can be observed from Figure 1.2 that among the different interoperability layers, domains and zones, SG will be comprised of a number of different functions/applications to ensure reliability of the power supply. Thus, a huge number of controllers plus intelligent metering devices with varying functionalities and requirements will be required to accomplish the goal(s). These controllers include, but not limited to, voltage/reactive power controller, frequency controllers, power balancing controllers etc., each with varying requirements for information access, data size, latency, information

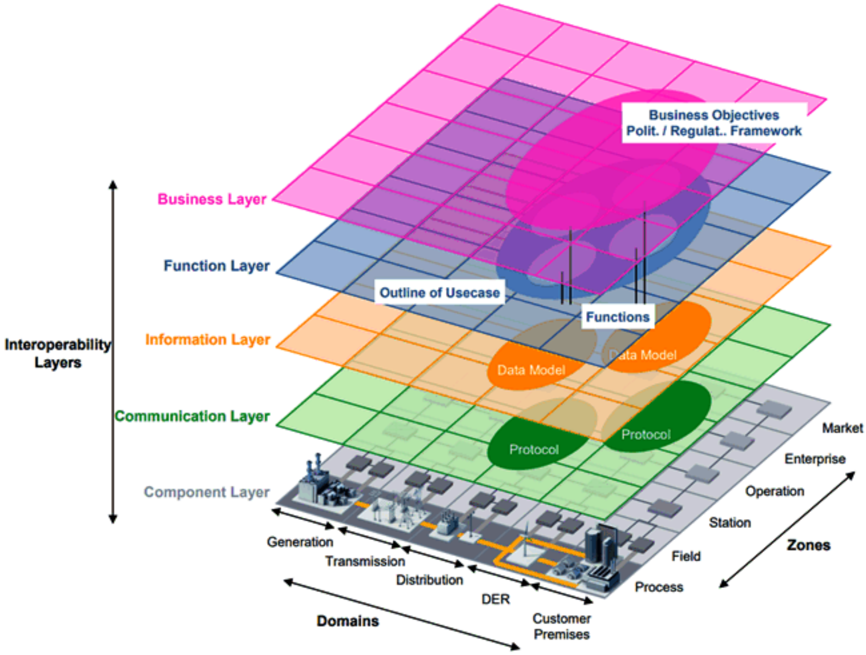

Fig. 1.2: Smart Grid Architecture Model Framework [8]

loss are to mention a few. Consequently, the underlying communication networks must not only allow the passing of information between all entities in the SG but also ensure that the controllers receive the information actually required to carry out correct actuation. While considering communication networks in a SG scenario, although any network imperfection can influence the control performance, but two network effects are worth exploring i.e.

1. Information quality degradation, and
2. Information loss

Delays in communication network lead to increase in information age that can become a reason for information quality degradation. It is pertinent to mention here that information age refers to the end-to-end age of information, which is the sum of all delays caused by the network as well as ICT components. This is in particular not good for time critical applications where higher information age may lead the controller to carry out actuation based on old information. Similarly, information loss or more precisely the loss of message containing information about status update or control actuation may lead the system not reacting when required. Both higher information age and information loss may end up in a sub-optimal control performance or in worst-case blackouts in part of the power grid. This calls for an exhaustive investigation to determine the trade-off between information loss, loss of information quality, and resources spend on limiting those impacts before any communication setup and related protocols are realized for the controllers to be used in critical infrastructure, as SGs.

1.5 Research Question

As stated in Section 1.3, two ancillary services (or grid support services) from ReGen Plants have been considered in this dissertation. Technical details and other related information of the selected ancillary services will be provided in Chapter 3. It is important to note that the scope of this dissertation is not to design appropriate controllers for the provision of selected ancillary services. However, in this dissertation, these ancillary services have been considered to address the following broad research question:

What is the impact of communication in providing coordinated voltage/reactive-power and frequency/active-power stability supports from ReGen plants?

The following chapters elaborate on how this research question is addressed by dividing it into several sub-questions.

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Chapter 2

Role of Communication technologies and Research Challenges

This chapter will briefly explain the role of ICT along with the related actors in the provision of online grid support services (also known as ancillary services) from ReGen plants. The explanation will be followed by the state-of-the-art in this regards and finally the hypothesis asserted in this dissertation will be put forth.

2.1 Communication Actors in the provision of Ancillary Services

Figure 2.1 defines the general system architecture for RePlan project, including the power system structure and its assets, the communication layer and the involved actors having roles and responsibilities for providing ancillary services.

From Figure 2.1, it can be observed that in addition to the ReGen plants, there are several other actors involved in the provision of ancillary services from these power plants. These actors are broadly characterized as:

1. Technical performance players (such as DSO, TSO, Aggregator etc.)
2. Market players (such as forecast provider, retailers etc.)
3. The actors that are in charge of the communication network infrastructure i.e. ICT actors (such as Access network provider, wide area network provider and access network owner)

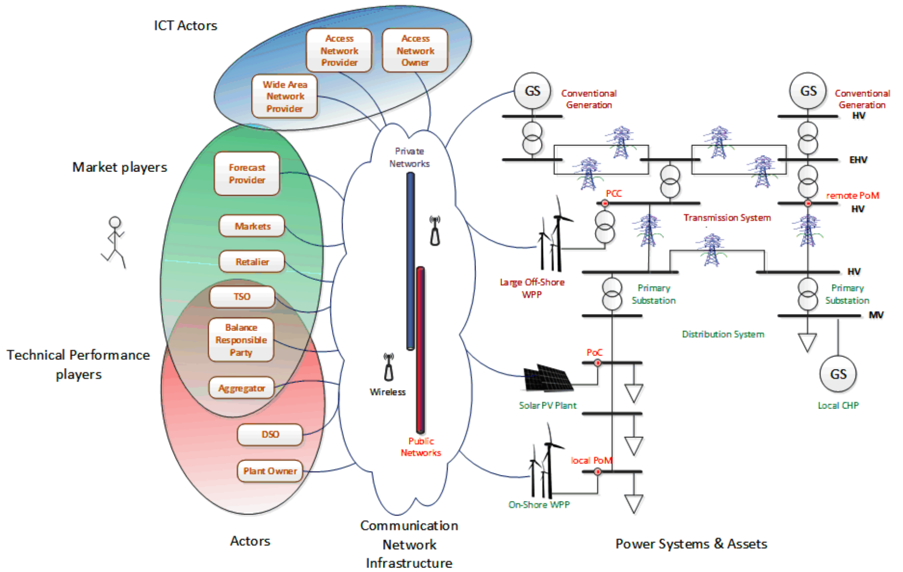

Fig. 2.1: General system architecture including power system & assets, control levels, ICT layer and actors [19]

Incorporating power system with different actors require collaboration among experts from several areas, in addition to the power related researchers/ engineers. The pertinence of this collaboration lies in the fact that there are significant differences in, for instance, communication as well as electrical related equipment, e.g. messaging protocols, information models, reliability requirements, hierarchy etc. [3]. However, since this dissertation mainly focuses on the communication aspects related to the provision of AS, the actors associated to the ICT are further described and explored in following subsections.

Communication between the different entities in the system, as illustrated in Figure 2.1, is critical for the operation of the system. Therefore, while considering a communication network for SGs in general and particularly for the provision of AS from ReGen, there are several questions that need to be answered. For instance, **a)** what are the different grid assets involved, **b)** what are the most suitable communication technologies and, last but not the least, **c)** does it require to build a new communication infrastructure or it can rely on the already existing ones. Building a new network communication infrastructure will give benefits in terms of having a privately owned network dedicated to SG applications, however at a cost of huge investment. Secondly, private networks are relatively simple to control, entities can be scheduled for data transmission, and the overall data packet rates are limited to a known number of devices each producing a well-defined traffic pattern. If the network, on the other hand is public, then these are usually shared networks, and in principle, there is no control of what goes on. Certain network operators provide Quality of Service (QoS) as a way to provide priority to a certain classes of traffic when traveling through the network. It is also expected that such priority services become more relevant as business cases as machine-to-machine (M2M) communication (as in SGs), becomes a reality. In this context, it is also important to understand the role of each of the ICT actors involved in the provision of the AS from ReGen plants.

As shown in Figure 2.1, there are following three main actors that are important to be considered for the aforementioned scenario:

2.1.1 Access Network Provider (ANP) [19]

As the name implies, ANP is the operator of the communication network, i.e., provider of telecommunication services, e.g., wireless access from a ReGen plant controller to the control center. While, access network (AN) is the communication network that provide the last mile connection to the different entities involved in the system operation and can rely on both wired and wireless networks. Traditionally wired connection has been a prominent solution due to its inherent reliability, but is usually also very costly due to deployment costs. Wireless embedded M2M solutions for utility automation are becoming increasingly important as a possible solution to connect the involved entities. Leveraging on established connections with end users using wired/wireless connectivity and on cost efficiency for deploying and offering a more flexible connectivity to the system operators, the telecommunication companies will play a vital role in common applications such as [6, 19]:

- Supervisory Control and Data Acquisition (SCADA)
- Automatic Meter Infrastructure
- Home Energy Management
- Electrical Vehicle Charging
- Distribution Automation
- Demand Response

In addition, the ANP can supply connectivity services to the DSO and TSO for monitoring and managing SG equipment. Depending on business conditions (based on CAPEX and OPEX), the provided connectivity services could be extended to an integration between the ANP network and its enablers, the DSO/TSO communication network and grid. In this case, ANP can also enable a series of market driver, positively affecting the SG business case. Alternatively, a DSO could also take the role of ANP themselves, but this requires the DSO to take additional responsibilities of properly handling the data in network [19]. Business models for driving M2M platforms for access to the different entities is not in the scope of this dissertation, as the focus is rather on the impact of using different technologies, wired as well as wireless in the AN and to what extent these technologies can support the different control functionality and under which conditions. This includes both private as well as public type networks. The analysis made in this dissertation will therefore be helpful for the ANPs to understand the communication requirements and associated aspects for the selected ancillary services.

2.1.2 Wide Area Network Provider (WNP) [19]

The WNP is defined by its ability to provide long-range connectivity, and is constructed by several networks in connection to each other. Typically, Wide Area Networks (WAN) are provided by tele-operators as well as connection to the established Internet (which also can be defined as a WAN). Thus, WNP is the operator of the highest level of networks represented by WANs covering large areas. WANs extend beyond the boundaries of the personal space (Personal Area Network - PAN), buildings/premises (Local Area Network - LAN) and cities (Metropolitan Area Network - MAN). Technologies at this level mostly include fiber cables, due to their physically large footprint, which necessitates a medium that can sustain high data-rates over long distances through low attenuation and relatively high resistance against noise. ATM, SONET/SDH, X.25 and Frame Relay are commonly found at the backbone of WANs. In most cases for M2M type of traffic, this is handled by a single network operator, but co-cooperation with other companies are also seen in specific cases, however with potential complications in the exchange of data packets on the boundaries between the different operators.

For this dissertation, complex business or interrelations between different operators as such are out of the scope, and the focus will be on technical aspects, defining and assessing different cases and scenarios for reliably and timely provide the service required in an end-to-end communication setting. In this regards, the focus is laid on the end-to-end properties, such as delay characteristics and packet loss probability. It is also assumed that the data traffic flows are stochastic in nature due to the aggregation of data traffic from/to the access networks. Further, this dissertation shows how the controller's performance is affected by the selection of transport layer protocol under imperfect network conditions while offering different levels of end-to-end data transportation service quality to the applications. Thus, the analysis presented in this dissertation will provide WNP with insight into the fact that the selection of transport layer is a trade-off between either making an information delay tolerant or loss tolerant.

2.1.3 Access Network Owner (ANO) [19]

As the name implies, ANO is owner of the communication network on which the ANP operates, where one entity may overtake both roles. Typically when using another company's network, there is no or little control of the data packets, and mostly the "best effort" traffic can be achieved. Special agreements can ensure data prioritization, however at a larger cost.

In this dissertation, it is assumed that the operator also owns the network, as this gives the freedom to explore the technological capabilities. Furthermore, it simplifies the interaction between actors which otherwise is needed to be accounted for. At worst, it will be a differentiation between being able to adjust QoS metrics and not being able to do so, which is most often the case if an operator is renting another company's network for increasing its own coverage and penetration.

The state-of-the-art in this regards is presented in the following:

2.2 State-of-the-Art

In order to get a future resilient power system with 100% RES by 2050, there are several challenges and milestones to be achieved. For instance, renewable generation plants require an extensive exploration of ancillary services they can provide with the capabilities of having coordinated control, fast and reliable communication as well as the forecast of the available power. The delivery of ancillary services from ReGen plants "online" highly depend on the communication technology and a reliable forecast of the power availability. Under the RePlan project controllers were developed for the delivery of AS from ReGen plants that are based on state-of-the-art methods to simulate of renewable generation patterns and wind power forecast methods. Since these ancillary services rely on communication network infrastructure in the control loops of the plant models, this dissertation explores and assesses communication networks as well as investigate their impact in providing coordination and ancillary services from ReGen plants.

The communication requirements for different applications in a SG scenario greatly vary, causing a variation in the choice of relevant communication technologies. Moreover, the technologies/standards vary based on different regions. For instance, Power Line Communication (PLC) have mostly been opted in Europe for smart meter communication [20], while in the USA, wireless technologies are prevalent [18]. Similarly, IEC-61850 is the most important communication standard for electrical substation automation systems used for smart grid communication in Europe, while that in the USA is DNP3 [18]. References [1, 10, 13] indicate several different communication technologies that are appropriate to be used in SG communications. Where, the authors in [1] conclude that choosing a single optimal technology for the communication in SG is difficult because of the large difference in price of the technologies as well as the lack of cost benefit analysis of the technologies in a SG scenario. This dissertation, therefore, assesses the impact of using specially the public network communication infrastructure (see Publications [A], [B], [C] and [D]) and IEC-61850 standard (see Publications [E], [F] and [G]) for providing AS in a SG scenario.

Reference [8] defines the monitoring architecture and fault management approach for the project named SmartC2Net. Based on state-of-the-art analysis and requirement identification, [8] proposes design for the monitoring of networks as well as the grids, mostly focusing the low voltage (LV) side of the grid. The designed model integrates and couples grid and network monitoring subsystems. A fault management system, later defined in [8], uses the monitoring system to monitor the communication network to detect complex accidental issues/anomalies and malicious attacks. While, [9] defines active monitoring mechanisms and grid information support systems based on the adaptive monitoring system performing measurements related to communication network and power grid. These measurements are also made on the fault management system detecting and predicting network/grid issues for the same project. As far as the fault detection and handoffs are concerned, according to [7], these fault issues can be resolved by using high diversity of available access networks with different technologies, infrastructures and operational characteristics for end-nodes operating in emerging networking scenarios. The authors in [7] conclude that the control decisions must be made at the network edge, encouraging the approach of fault management driven by the end-nodes.

The proposed concepts and the results obtained in [8], [9] and [7] have provided theoretical and practical grounds in developing a network model for the provision of reliable coordination and AS from the ReGen plants. However, the problem in each case has been addressed for a specific SG application that cannot be generalized to all applications/networks to address all types of cases. This dissertation specifically focuses on the provision of two AS, namely voltage/reactive power control coordination and frequency/active power control coordination from ReGen plants. Furthermore, contrary to the case in [8, 9], the focus in this dissertation was on medium voltage (MV) grid for the provision of voltage control coordination (see Publications [A], [B] and [C]), while an entire power system was considered for assessing the communication impact on frequency stability support (see Publication [D]).

In [2], the authors develop analytical models for three different information access strategies based on a quality metric called mismatch probability ($mmPr$). Reference [2] defines $mmPr$ as "The probability that any of the N values of the information elements that are used at the requester does not match the current true value at the remote location". While the information access strategies addressed are: reactive, proactive (event-driven) and proactive (with periodic updates). As far as a single information provider is involved, the reactive and the proactive (event-driven) access strategies perform the same [2], but this difference increases significantly with the scaling capabilities. The quality metric mmPr has extensively been used in context of the applications related to SG communication but also for applications other than SG (see for example, [16, 17, 22]). In fact, the concept of *mmPr* originates from non-SG applications in terms of context awareness, where the common factor is the access to dynamic information. The benefit of using *mmPr* in context of SG applications is that it combines the impact of network delays, information access methods along with the event rate in a single scaler value and put those in relation to the SG scenario. In [11, 12, 23], it has been concluded that *mmPr* is a useful link between SG control performance and communication network conditions. While references [4–6, 15] show that it is possible to improve performance of a SG controller by choosing an optimal information access strategy, where *mmPr* can be a useful quality metric in selecting this optimal information access strategy. Similarly, the author of [14] has adopted the *mmPr* concept for establishing access scheduling methods for periodic controllers.

In the references cited above, *mmPr* has mostly been used to somehow adapt controllers according to the network conditions. However, in contrast to the previous work, the same quality metric (*mmPr*), based on the proactive (periodic) access strategy, has been adopted in this dissertation to determine if changing the network parameters/protocols can help improving the controller's performance in terms of providing reliable information. Here, it is worth to mention that the definition of "reliable information" varies application to application. For instance, for time/delay critical applications, the most recent information is the most reliable one. While, higher delays in communication increase the information age and thereby effect reliability of information. It is also important to note that information/message loss can also be seen as infinite delay time, and thereby mapping it into an extreme delay. Although, for a TCP type protocols, the loss message/packet can be recompensed by a re-transmission, but for time/delay critical applications, it is essential to answer the question like:

- How to differentiate between extremely long delays or losses in the network?
- Is it worth to spend time for retransmission or wait for the delayed message?

Thus, these questions give rise to the fact of having trade-off with regards to spending time on retransmission or wait for delayed message along with the policies (such as adjustments of time out values) around that. Since transport layer protocols (UDP and TCP) are responsible for providing different levels of end-to-end data transportation service quality to the applications [21], these are the two common ways to approach the issue, i.e., either accept loss in transmission or pay in terms of retransmission. Therefore, by using mmPr as an information quality metric, this dissertation focuses on TCP and UDP to show that selecting a transport layer protocol is in fact a trade-off between making information delay tolerant or loss tolerant (see Papers [E], [F] and [G]).

2.3 Research Statement

Since a communication link between the ReGen plants and the system operators does not exist in today's power grid, a communication infrastructure must be first implemented before the provision of AS can be realized. Implementing a new infrastructure with high-speed connection, such fiber optics, dedicated for this purpose would be very expensive, and is not feasible. However, using an existing general-purpose network communication infrastructure, although shared with a number of users, can be considered as a potential candidate to get required communication network performance. Therefore, the main objective of this thesis is to assert the hypothesis that:

General-purpose networks and their related protocol stacks under challenging conditions can really support the provision of AS from ReGen, if properly configured.

There are two parts of this hypothesis; the first part i.e. "*General-purpose networks and their related protocol stacks under challenging conditions can really support the provision of AS from ReGen*" lead to assess the impact of general purpose networks in the provision of selected AS and evaluate the control performance. While for the second part, i.e. "*if properly configured*", this dissertation focuses on the configuration of protocols (and not the network itself). This part directs to explore if the considered communication networks can be considered to be an active resource offering QoS provisioning. This lead to focus on selecting a scheme (protocol) that balances higher loss in information exchange with time-consuming acknowledgment based schemes that provides reliable information exchange.

Therefore, this hypothesis leads to several questions that are used to guide the studies performed in this dissertation:

1. What is the impact of using general-purpose cellular network communication in providing coordinated voltage/reactive-power stability support from ReGen plants?

2. What is the impact of using general-purpose cellular network communication in providing coordinated frequency/active-power stability support from ReGen plants?

3. How does delay and loss of information in a communication network affect the provision of the two selected ancillary services?

4. How can *mmPr* as an information quality metric be linked to the provision of AS from ReGen?

5. Can we use the *mmPr* as a source of trade-off between QoS parameters to increase to the reliability of communication?

Figure 2.2 shown on next page maps in which publications these questions have been addressed.

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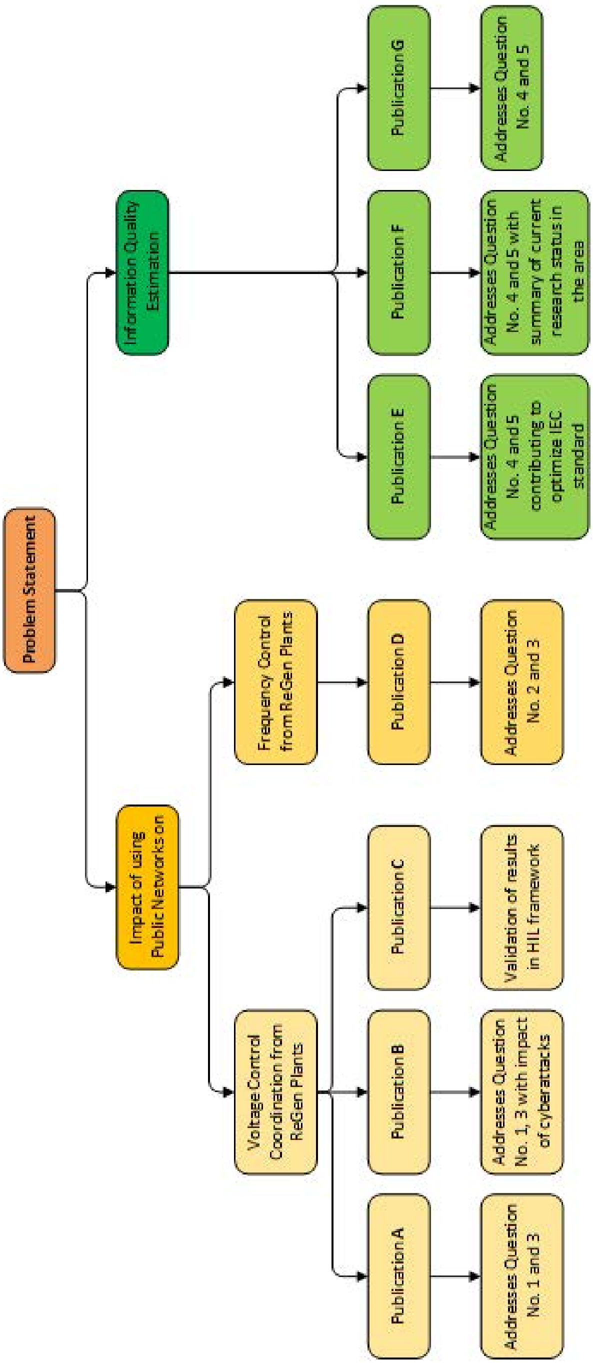

Fig. 2.2: Flow chart showing the division of main problem statement into sub-questions and to which publication these questions have been addressed.

Chapter 3

Evaluation Framework and Methodology

As ascertained in Section 1, two AS are considered in this dissertation that are needed to ensure the system stability, comprising both transmission and distribution level, detailed in [4, 20]. These AS vary in their scope and importance for the electrical grid stability. Thus, the requirements imposed on the ICT infrastructure should reflect the range of applications. However, a common requirement shared by both services is a reliable and secure communication network infrastructure. The individual ancillary service therefore has to be able to deal with impairments up to a complete breakdown of parts of the ICT infrastructure. For instance, if an interface exhibits increased latency, possibly due to network congestion, this has to be detected and acted upon. This chapter, therefore, introduces the background and concepts related to the individual use-case scenario opted in this dissertation and presents the summary along with few main results of related publications.

3.1 Voltage Control Coordination from ReGen

This section aims to present and discuss the relevant background required to answer Question 1 from the problem statement in Section 2.3 i.e. "What is the impact of using general-purpose cellular network communication in providing coordinated voltage/reactive-power stability support from ReGen plants"? The background and related discussion presented in this section will help readers to understand various issues and challenges associated to the provision of voltage stability support in power systems with large penetration of ReGen. These challenges are addressed by considering real measurements related to the power system given by a local DSO in Denmark as well as real measurements related to the communication network infrastructure. Based on the actual trend of increased penetration of both WPP and PVP, the expected future challenges are illustrated by means of exemplary benchmark distribution grid (BDG).

3.1.1 Background

Today, onshore WPPs are the major source of wind power in Denmark (i.e. around 3799 MW) [1, 19]. These WPPs are connected to medium voltage grid and are distributed individually or in small-scale clusters. Additionally, Denmark has the biggest PVP (to-date) in Scandinavia of 61 MW that was commissioned in December 2015 near Kalundborg [3]. Keeping in mind the 2050 goal of the Danish government (i.e. a 100% renewable based power production), this contribution from WPP and PVP will continuously increase, with a major share from WPP. The foreseen trend is that in coming years, the increased share of installed ReGen plants will mainly be accomplished in MV distribution systems by new generation WPPs along with large-scale concentrated PVPs (see Publications [A] and [B]). However, it is important to notice that since the power production based on wind and solar PV depends on weather conditions, in Denmark it faces large variations due to the varying wind speeds and fast moving cloud conditions, respectively. Thus, large voltage fluctuations are expected at the point of connections. The voltage levels may drop due to certain load types or increase due to generators in the grid or by reactive power shortages. Depending on the available amount of generation and consumption, the increasing penetration of ReGen plants into the distribution systems may also reverse the power flow, which also leads to increasing voltage levels [17, 19]. Voltages above nominal values particularly occur during high wind conditions and high solar irradiation, combined with low-load situations [19]. At the same time, as per the grid code requirements [8], the voltage profile should remain close to the desired profile ($\pm$10%) and within the tolerance band margins with a time frame of hours [19].

Figure 3.1 illustrates the impact of changing solar irradiation on the voltage levels measurements for three consecutive days [19]. These voltage measurements include voltage and active power for one PV system of 6 kW from a secondary substation connecting several PV systems. It can be observed from the daily power profile that voltages rise up to almost 1.05 pu during midday time of the first day, when solar irradiation is high (**Note:** According to [8], for the 400 kV grid Voltage level the reference 1 pu value is 400 kV, for other grid Voltage levels the reference 1 pu voltage may differ for each TSO in the same synchronous area). From Figure 3.1 it can also be anticipated that the load consumption at the first day is relatively low in contrast to the following two days, where the voltage rise during midday is less significant.

Nevertheless, from the exemplary power profile for just a single PV system, it can be established that a large number of PV systems at household level can have a significant impact on the voltage levels as seen in the secondary substations (MV/LV) and hence influencing the MV grid.

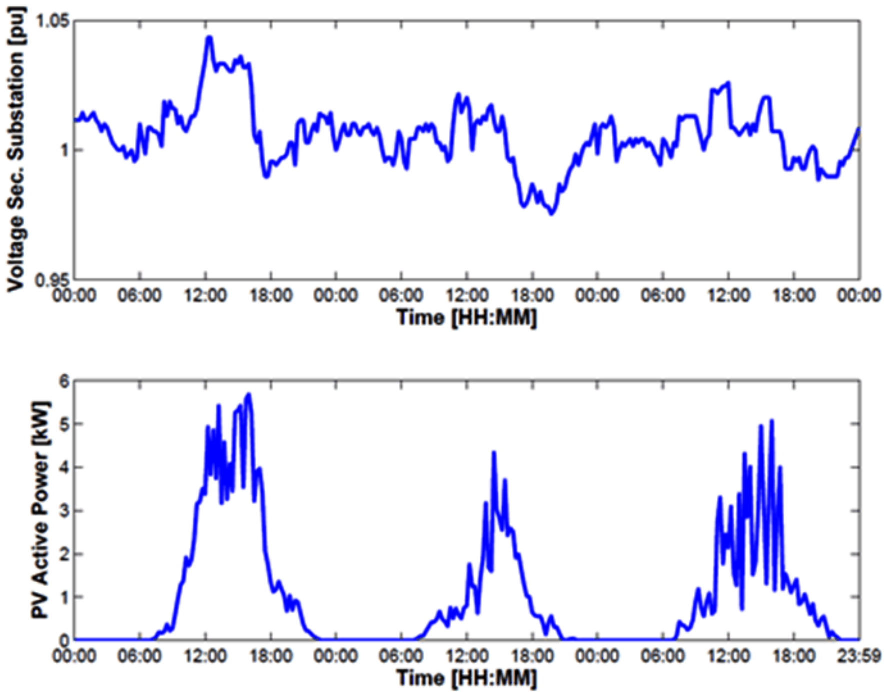

Fig. 3.1: Voltage profile at secondary substation and power profile of one PV system (15 minute values) [19].

As ascertained above, the foreseen trend is that in coming years, large portion of installed ReGen plants in Denmark will essentially be achieved in MV distribution systems by WPPs along with PVPs [21]. For instance, 500 MW of additional onshore capacity will be accomplished by scraping 1300 MW of outdated onshore wind turbines and installing of 1800 MW of modern wind turbines with improved controllability [22]. While, current PV generation capacity of Denmark (i.e. 908 MW to-date [2]) is planned to be increased to 1000 MW by the year 2020. This increase in PV generation capacity will primarily be accomplished by commercial/industrial rooftop PVPs and ground mounted systems in the MW range [22]. Thus, based on the measurement for a single 6 kW PV system in Figure 3.1 as well as those available for wind power in [19], it can be anticipated that a combined effect of large power variations from large PVP along with WPP in a MV feeder may lead to very large voltage fluctuations approaching or even exceeding the voltage limits of $1.1pu$ especially in low load situations. With voltage levels exceeding certain boundaries, not only the disconnection of ReGen units is expected with a consequence of loss of production and thereby loss of earnings (market interferences etc.) but these may also damage other equipment such as transformers, customer loads etc. The Danish Energy Association is, therefore, concerned about these voltage excursions due to the increasing number of ReGen in the distribution grids (DG) as many DSOs especially in Jutland have started to experience this phenomenon [19].

There are several methods to control the voltage/reactive power, for instance [19, 21]:

1. Using capacitor banks and inductors
2. Using On-Load Tap Change (OLTC) transformer
3. Advanced solutions using power electronic devices (PED)

Although the first method is a cheap solution but it has several downsides, such as limited number of switching per day [21], power quality degradation during switching times, solving the voltage issues locally and not focusing the voltage profile on the entire feeder etc. [21]. Similarly, in case of an OLTC transformer, compared to the variation in voltage profile, the time required to change a tap position is quite slow (ranging between 3-–10 seconds [7, 21]). Moreover, according to [12], around 56% of the total failures in a transformers are caused due to these tap changings [21]. Therefore, OLTC transformer will not be a feasible solution in the said scenario. Companies like Siemens and ABB also provide PED based solutions for voltage control but those are mainly dedicated to the LV applications that too at the cost of huge investment (i.e. the cost of a single device is 3–4 times higher than that of a transformer at secondary substation [21]). The CAPEX and OPEX related to the PED based solutions available for MV applications are again not attractive for the DSOs except no other solution exist [19].

3.1.2 Voltage/Reactive Power Control Coordination from ReGen

In current situation, where other available solutions are not viable, a simple solution proposed in [19, 21] and used in publications [A], [B] and [C] is to take the advantage of today's ReGen plants to provide reactive power support. The benefit of using existing ReGen plants for this purpose will not only help to down-regulate the entire voltage profile in the distribution grid but also maintain the voltage within the desired limits at the nodes [19, 21]. As ascertained in Publication [A], the aggregators of these ReGen plants are foreseen to take the responsibility of voltage/reactive power provision. Thus, the generic possible coordination scheme between the aggregator level and the ReGen level for distribution grid proposed for the RePlan project in [19] and also used in Publications [A], [B] and [C] is illustrated in Figure 3.2.

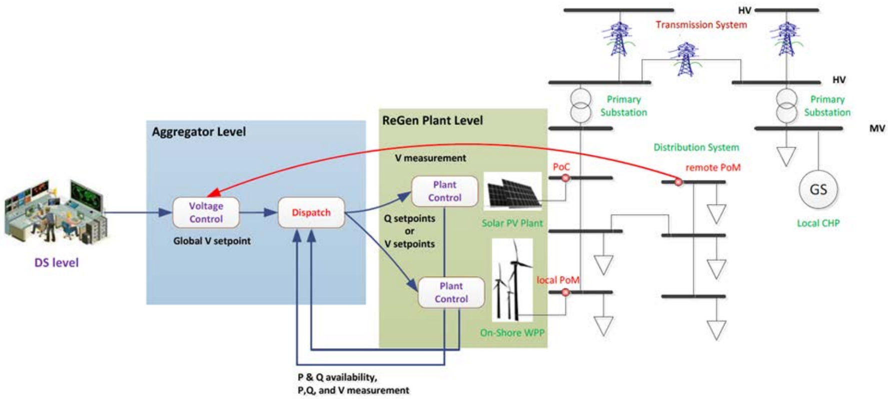

Fig. 3.2: Control coordination by means of voltage control [20]

Following terms need to be understood before going into the details of how the control coordination scheme for voltage control works in Figure 3.2:

- **Control Coordination:** According to [20], the term "coordination" for voltage control refers to "the allocation of resources to deliver a given service, taking into account the real time communication and the whole control levels chain".

- **Local Point of Measurement (PoM):** A point in the public electricity supply grid, which is located closest to a particular plant and can be used within the control system for a certain ancillary service to be provided. It can be voltage, power or frequency measurement [20].

- **Point of Connection (PoC):** This is a point in the public electricity supply grid, where a power generation plant is (or can be) connected [20]. It is worth mentioning here that the local PoM may electrically coincide with the PoC [20].

According to [19, 20] (as shown in Figure 3.2), the voltage controller at the aggregator level receives measured voltage signals from the PoM in the remote bus located far away from the substation. In case there are many loads connected to this bus and has high voltage variations, it will be a critical bus. Now in order to support this bus, the voltage controller produces a global voltage/reactive power set-point to the dispatcher and delivers relevant system data to the dispatch block. The dispatcher can distribute this set-point to every allocated ReGen plant as voltage, reactive power, or power-factor set-points accordingly. The input to the dispatcher can be the available active and reactive power together with active/reactive power/voltage measurement signals from ReGen plants (i.e. from PoC).

For the provision of voltage stability support from ReGen plant, the variable output of these plants will be the main limiting factor. Thus, it will be crucial for the aggregator to maintain an overview of the state of the portfolio to be able to track service delivery and activate correct control actions if the defined boundaries for the plants are exceeded. Additionally, it should be noticed that the exchange of measurements from a ReGen plant as well as the set-points from aggregator level in the "control coordination" are highly influenced by the underlying communication network infrastructure. Thus, selection of an appropriate communication network will play a crucial role in the control coordination scheme.

3.1.3 Communication Network Infrastructure

As ascertained in the above section, the aggregator controller receives voltage signal from the ReGen plants and sends back the set-points accordingly, this requires the plants to have a resilient online coordination with the aggregator control unit which, however, depends on the underlying communication network infrastructure. Latency, data rate, redundancy, serviceability, reliability, costs of deployment and ownership are the factors that define the requirements and finally lead to a choice of technologies that could be used for this purpose. To comply with all such requirements and keeping in mind the huge penetration of the ReGen plants in coming future, the benefits associated with existing public cellular network communication infrastructure make it a viable candidate for this purpose. Publications [A] and [B] indicate/highlight the benefits of this network infrastructure as compared to the other communication networks and technologies. However, since these public networks were designed keeping in view the human-type communication (HTC), a lot of research is still required before these such networks fully support the machine-type communication (MTC), as in said scenario. In this context, to be able to support the voltage/reactive power control coordination from ReGen plants, there are several challenges to be addressed, i.e.:

1. Can the public network communication infrastructure support the provision of voltage control coordination with current settings?

2. Does the communication properties (such as end-to-end delay, information loss probabilities etc.) offered by these communication networks meet the requirements imposed by the provision of voltage control coordination?

3. In case of using public network infrastructure for the said scenario, what will be the impact on, for example, power losses if communication network fails to operate?

4. In case of a cyberattack, what will be the impact on the power system performance?

5. How to come up with a suitable communication network model that represents real communication network and can be effectively linked to the power system model?

6. Is the designed simulated communication model valid (when compared with a real-time HIL based model)?

These questions have been answered in three different publications i.e. [A], [B] and [C]. In all these publications, not only a real BDG was taken into account but also the communication properties were considered by taking into account the same grid area where the BDG resides i.e. Støvring area in Region Nordjylland in the geographic region of the Jutland peninsula known as Himmerland in Northern Denmark. Topologies and basic information about the same geographical area has been used as a basis for all assessments. Figure 3.3 shows a GIS map for the BDG containing primary substation, ReGen plants (WPP, PVP 1, PVP 2 and PVP 3) and placement of communication masts.

As can be seen from Figure 3.3 that there are several communication masts around the grid assets. Regarding the aggregator control unit (that could be a hardware unit) can be placed at the primary substation or far away somewhere else in Denmark at any control center, as shown in Figure 3.4. The distance between communicating entities (i.e. ReGen plants and aggregator) can be one of the external influences on latency as well as other communication properties presented in [20]. Thus, in addition to the network utilization (in terms of number of users), this distance may also have an impact on the time a signal (message) takes to travel between ReGen plant and aggregator, especially when both operate on different carrier networks.

3.1.4 Transport Layer Protocols

While connecting the ReGen plants to the aggregator unit using the existing public networks, it has been ascertained that the bandwidth, data rate, and other such communication properties are sufficient enough to carry out the data between end devices. However, as mentioned in Section 1, the focus in this thesis is mainly to explore if public cellular networks can really meet the end-to-end communication requirements such as latency and packet loss probabilities or not. For this, since the transport layer plays an important role in delivering the end-to-end data transportation services, the two main

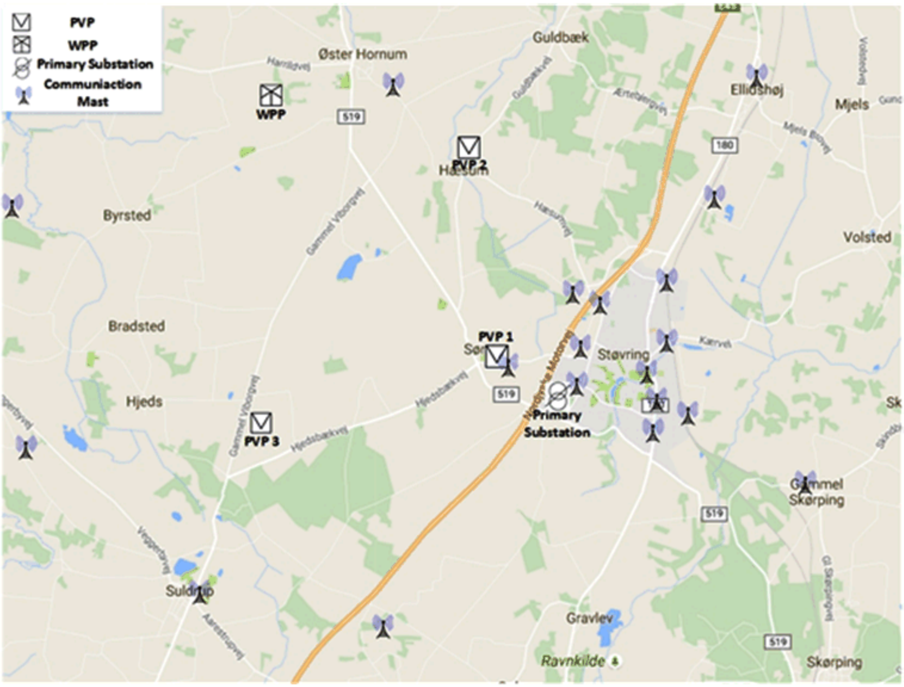

Fig. 3.3: Layout of primary substation, ReGen plants and masts for wireless communication in the benchmark grid area [19]

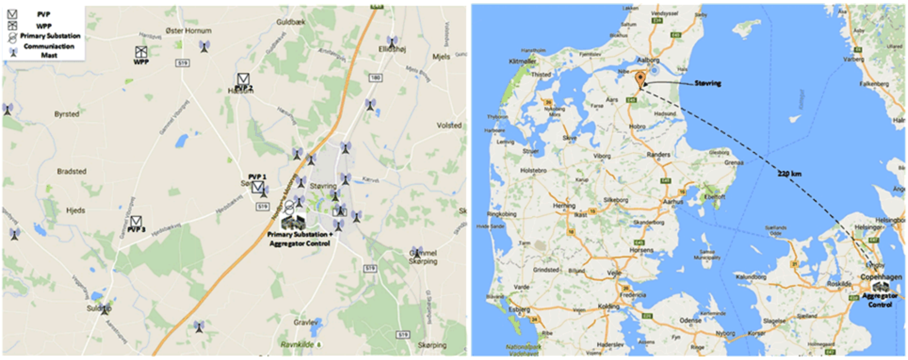

Fig. 3.4: Concept of communication approach when aggregator is **(a)** placed at local primary substation and **(b)** placed far away from the local primary substation.

transport layer protocols i.e. transmission control protocol (TCP) and user datagram protocol (UDP) were also take into consideration. Publications [A], [B] and [C] elaborate on how the real measurement based on end-to-end delay traces (including packet loss information) were captured specifically from the benchmark grid area. It is important to note that these end-to-end delay traces were captured via different public networks available in the area (with public settings and not M2M or privately owned networks). Moreover, although the delay traces were captured for both TCP and UDP, as shown in Figure 3.5, the assessments for the voltage control coordination was only done based on TCP only. The reason for using only TCP is that IEC-61850 and other related protocols and standards communicate over the TCP/IP protocol.

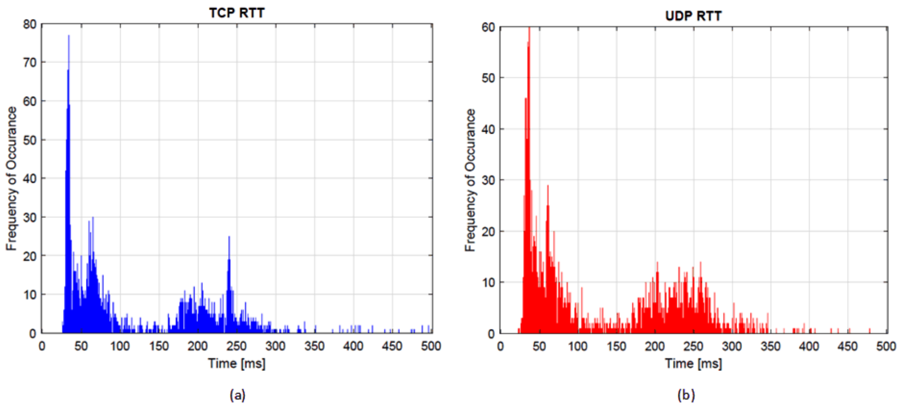

Fig. 3.5: Figure showing the RTT distribution for **(a)** TCP and **(b)** UDP measured around the benchmark region.

3.1.5 Related Publications – Summary

The challenges and questions raised in Section 3.1.3 are addressed in the following three publications:

Publication A: On the impact of using public network communication infrastructure for voltage control coordination in smart grid scenario.

As the name implies, this paper shows the impact of communication on online voltage control coordination in distribution grids using existing public network communication infrastructure. Based on a real BDG and the network traces obtained from the benchmark grid area, several test cases have been introduced and evaluated regarding the related latencies and validity of the signals being exchanged between aggregator and ReGen plants. The impact of these network imperfections on the said scenario is then mapped into power losses into the system. This paper shows that end-to-end communication delays in the range of seconds to minutes have a minor impact on the resulting power losses. However, the delays up to several hours, due to connection failure or even cyberattacks, may lead to higher power losses in the grid. Thus, the results in Publication [A] reveal that the design and tuning methodology for voltage/reactive power control must account for the delays/failure of the ICT especially when considering public networks. These results contribute to provide guidelines for the DSOs related to the ICT based issues in the provision of voltage control coordination from a large number of ReGen plants in future power grid.

Publication B: On the impact of cyberattacks on voltage control coordination by ReGen plants in smart grids.

While using public networks for communication in critical infrastructure such as power systems, it should be made secure enough such that it is saved from the possible cyber-attacks. Secondly, it should also be known that to what extent the cyber-attacks could sabotage the whole system. For this reason, this paper highlights the possible impact of cyber-attacks on online voltage control coordination from ReGen plants. In Publication [B], again the assessment is based on the BDG. It evaluates various aspects related to the cyber-attacks especially with respect to the related latencies and validity of the signals being exchanged between aggregator and ReGen plants that could result in deviating voltage control performance in the distribution grid. Based on the criticality of power system infrastructure, two cyber-security solutions are also proposed in the end that can be used to mitigate cyber-attacks without effecting the performance of the power system. The results in Publication [B] reveal that the design and tuning methodology for voltage/reactive power control must account for the various cyberattack scenarios especially when considering public networks. These results along with the presented cyber-security solutions contribute to provide guidelines for the DSOs related to the security of the ICT infrastructure that will be used for the provision of voltage control coordination from a large number of ReGen plants in future power grid.

Publication C: ICT based HIL validation of voltage control coordination in smart grids scenarios.

The main goal of this paper was to validate the coordinated online voltage control algorithms that were considered in publications [A] and [B]. This was done via a real-time Hardware-In-the-Loop (RT-HIL) framework available at Smart Energy Systems Laboratory in the Department of Energy Technology, AAU. A model based design (MBD) approach in SGs has also been introduced in Publication C that proves to be an important methodology in the design and implementation of SG technologies, solutions and corresponding products. Based on MBD, the paper first addresses the validation of the proposed ICT model in Publications [A] and [B] and then validates the coordinated online voltage control concept. This paper shows that there was a deviation below 1% for the main variables involved in Publications [A] and [B] as well as in real-time studies. The results in this paper confirm the validity of the main assumptions regarding ICT behavior considered in Publication [A] and [B]. The proposed methodology will contribute to support the DSOs in the stability and security of the power supply by obtaining confidence in the new control approaches at the early stages of the development with realistic emulation of real power grid and communication networks including the respective data traffic.

3.1.6 Voltage/Reactive Power Control Coordination from ReGen — Main Results

In order to demonstrate the impact of communication in the provision of voltage/reactive power control coordination from ReGen plants different test cases were taken in account in Publication [A], [B] and [C]. Using the delay traces (for TCP) shown in Figure 3.5, it has been ascertained in Publication [A] that there was no significant impact on the resulting power profile. However, due to network congestion, failure in the communication system or even cyberattacks, the latency in communication may increase up from minutes to even several hours. Thus, for testing long-lasting communication failures, a benchmark test scenario with a time frame of 24 hour was applied in Publication [A]. Four test cases were considered in terms of hours of latency caused due to communication failure i.e.,

- 1 hour
- 6 hour
- 12 hour
- 24 hour

Figure 3.6(a) shows the line losses expressed as percentage of the total generated power by all ReGen plants, averaged over the simulation period of 24 hours, with and without various communication failures. It can be observed from Figure 3.6(a) that the power losses increase depending on the duration of the communication failure in the system. (**Note:** The blue-colored bars show the power losses without any voltage control. The red color shows off-line voltage regulation with maintained settings of the ReGen plant controllers that leads to considerable increase in power losses. While, green color shows online coordination via a communication network that leads to significant reduction of power losses.)

The results shown in Figure 3.6(a) also account for higher latencies caused due to cyberattacks (such as DDoS). However, cyberattacks may also be used to manipulate voltage or droop characteristics of the local voltage controller in the ReGen plants. Figure 3.6(b) illustrates the voltage and reactive power profile for a case when all droop values are set to 0.5%, leading to a very flat droop characteristic. The cyberattack is shown to be initiated at $t = 500$ seconds that leads to subsequent voltage oscillations. The WPP experiences a voltage exceeding the limit of $1.1pu$ at t = 524 seconds and needs to shut down. Voltage oscillations between all PVPs sustain until PVP 1 shuts down at $t = 795$ seconds due to over-voltage. For a case of cyberattacks in terms of manipulating voltage set-points, the readers are urged to see Publication [B].

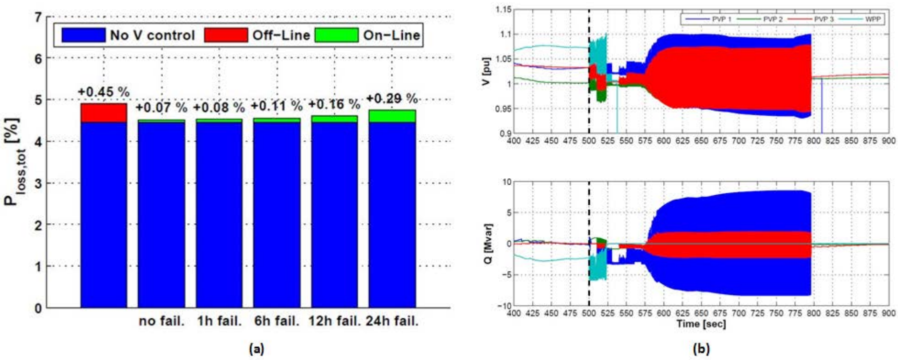

Fig. 3.6: Figure showing two main results from RTT distribution for **(a)** Average power losses over the simulation period for various durations of communication failure for updating the voltage set-points; and **(b)** V and Q of all ReGen plants when subject to a cyberattack (manipulating droop value at $t = 500s$).

3.2 Frequency Control Coordination from ReGen

This section aims to present and discuss the relevant background required to answer Question 2 from the problem statement in Section 2.3 i.e. *"What is the impact of using general-purpose cellular network communication in providing coordinated frequency/active-power stability support from ReGen plants"*? The background and related discussion presented in this section will help readers to understand various issues and challenges associated to the provision of frequency stability support in power systems with large penetration of ReGen. These challenges are addressed by considering an aggregated WPP model integrated into a generic power system model, specifically developed (in [5]) to assess the ancillary services in a relatively simple yet relevant environment. Moreover, real measurements related to the communication network infrastructure are used for the assessment in this dissertation.

3.2.1 Background

As ascertained in Section 3.1, the high penetration of ReGen plants in the current power systems will give rise to several challenges for a reliable and secure power grid operation [5]. Not only will the voltage control be an issue (i.e. keeping it within the grid code boundaries) but also controlling and maintaining the frequency of the overall power system within normal operation frequency variation intervals [5] will be a big challenge. The power system frequency is a measure of the balance between generation and load of electric power that depends on the speed of the synchronous generators. The value of this frequency should remain constant provided that the production from generators matches the amount of power required by the load [16]. The standard constant frequency in Europe as well as most Asian countries is set to $50Hz$, while in many North and South American countries it is $60Hz$. However, in case of a sudden change (decrease/increase) in the load, additional power has to be provided/consumed. This effect can be better understood via equation of motion of a synchronous generator in (3.1) [15]:

$$P_{mech} - P_{elec} = I\omega \frac{d\omega}{dt} \tag{3.1}$$

Here, P_{mech} is the mechanical power, P_{elec} is the electrical power, ω is the rotational speed, I is the moment of inertia, which is a constant that depends upon the material and size of generator. Equation (3.1) implies that an imbalance between P_{mech} and P_{elec} will result in a change in ω. The magnitude of this change for a given power imbalance depends on I i.e. higher the inertia, the smaller the change in speed. Thus, higher inertia in a power system can reduce the impact of sudden load imbalances and contribute to the frequency stability [15].

In this context, it is important to note that wind turbines (WT) in a WPP are the substantial non-synchronous renewable power generation source [15]. This is one of the main reasons that WTs do not inherently contribute to the frequency response as compared to the conventional generators [5, 15]. Furthermore, being decoupled from the power system, even the most modern WT (such as the VSWT – variable speed wind turbines) do not contribute to the system's inertia [5, 15]. Thus, by replacing conventional generators with the increase in inverter-based generation in future power systems, the synchronous inertia will be reduced (not being synchronously coupled to the grid) [5]. Consequently, the risk of high rate-of-change-of-frequency (ROCOF) following a loss of infeed or demand will increasing. This means, higher the number of VSWTs, lower will be the system's inertia that will ultimately lead to higher ROCOF during imbalances between power production and consumption [5, 15]. The ROCOF is a direct measure of system's strength to withstand sudden system imbalance after forced outages or system separations i.e. higher the ROCOF, higher will be the vulnerability of the system [5, 15]. Therefore, the risk of instabilities in the system or even disconnection of generation in distribution systems due to activation of ROCOF-relays will be increased. In case of severe disturbances, areas having large amount of power generated by wind will experience reduction in inertia that might be susceptible to frequency instability.

Hence, developing methods to improve system stability even with high shares of ReGen plants has been in the focus of academic and industrial research for the last couple of years. Moreover, the transmission system operators (TSO) have also started to analyze the power systems to improve their knowledge related to the entire system inertia [5]. One important area of research in this regards is the provision of "online" frequency control support and further investigate and analyze the possibilities of improving the overall frequency control support between WPP. It should be noted that the purpose of this dissertation is not to design control algorithm for the said scenario. The control algorithm has been designed in context of RePlan project and adopted as such in this dissertation. However, the goal in this dissertation and the related publication is to provide insights into the associated aspects, challenges and impact of communication in providing frequency stability support from ReGen plants.

3.2.2 Frequency/Active Power Control Coordination from ReGen

According to [5], following two VSWT are designed to control the active power via set-points depending on the wind speed:

- Doubly-fed induction generator with partial scale converter, also known as Type 3 WT

- Induction/synchronous generator with full scale converter, also known as Type 4 WT

With additional control implementation, WPPs that are equipped with such WTs can respond to the frequency deviations during a power imbalance. With different kinds of frequency deviations during a power imbalance, the frequency stability support in context of RePlan project is divided into the following categories:

- **Frequency Response (over frequency events)** – related to Limited Frequency Sensitive Mode – Over frequency (LFSM-O), which is active when the over frequency threshold is exceeded [5].
- **Frequency Control (under frequency events)** – related to Limited Frequency Sensitive Mode – Under frequency (LFSM-U) [5] and frequency variations within the normal operational boundaries. It is active when the under frequency threshold is exceeded as well as for frequencies generally deviating from 50 Hz. The frequency control can be further subdivided into:
  - **FCR (frequency containment reserve)** – also called primary frequency control, releases the automatic response to frequency changes with time over a period of few seconds.
  - **FRR (frequency restoration reserve)** – also called secondary frequency control. Activating FRR modifies the active power set-points/adjustments of reserve that provides units in the time-frame of seconds up to typically 15 minutes after an incident [5].
  - **FFR (fast frequency response)** – is related to inertial response.

For the details of each of the above-mentioned sub-categories of frequency stability support, the readers are suggested to see [4, 5, 20]. However, for this dissertation, only frequency control (for under frequency events) and that too for FCR (i.e. primary frequency control) is selected for further assessment and challenges related to the underlying communication network infrastructure, while the remaining one are left for future studies. Moreover, since WPP will have the largest share in the future renewable dominant power system and thereby the largest contributor to the system's frequency response; FCR from only WPPs is considered at this stage.

As for the voltage control coordination in Section 3.1, similar generic possible coordination approach has been implemented for the provision of frequency control coordination by ReGen plants, illustrated in Figure 3.7 (for the detailed description of the coordination scheme for frequency control, see Publication [D]).

Following terms need to be understood before going into the details of how the generic control coordination scheme for frequency control works in Figure 3.7:

- **Control Coordination:** According to [20], the term "coordination" for frequency control refers to "the scheduling of the assets to provide their contribution to a given service. This scheduling indicates reserve allocation (how much from each asset), order of their activation and the different moments in time when they are activated (i.e. delay in their response)."
- **Point of Common Coupling (PCC):** The point in the public electricity supply grid, where consumers are (or can be) connected. The PCC and the PoC (see section 3.1.2) may electrically coincide. The PCC is always located closest to the public electricity supply grid [20].

In Figure 3.7, the frequency controller in the aggregator level (can be directly controlled by TSO) receives measured frequency signals from the PCC in the remote bus. Now in order to support this bus, the frequency controller produces a global frequency/active power set-point to the dispatcher and delivers relevant system data to the dispatch block. The dispatcher can distribute these set-points to every allocated ReGen plant accordingly.

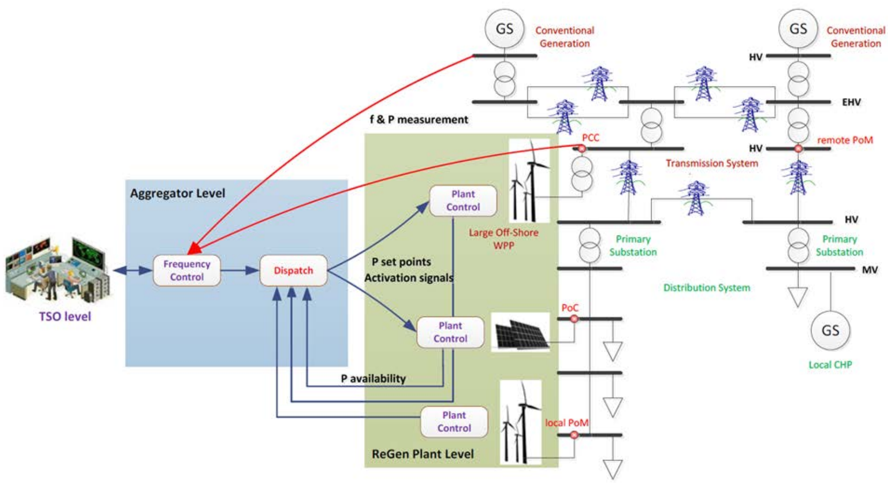

Fig. 3.7: Control coordination by means of frequency control [5].

For the provision of frequency stability support from ReGen plant, the variable output of these plants will be the main limiting factor. Thus, it will be crucial for the aggregator to maintain an overview of the state of the portfolio to be able to track service delivery and activate correct control actions if the defined boundaries for the plants are exceeded. Additionally, it should be noticed that communicating the real time measurements from a ReGen plant as well as the set-points from aggregator level play a crucial role in the control coordination scheme. In this context, to be able to support the frequency control coordination from ReGen plants, there are several challenges to be addressed, i.e.:

1. Can the public network communication infrastructure support the provision of frequency control coordination with current settings?
2. Does the communication properties (such as end-to-end delay, information loss probabilities etc.) offered by these communication networks meet the requirements imposed by the provision of frequency control coordination?
3. In case of using these networks for the said scenario, what will be the maximum network degradation (in terms of end-to-end delay) that effects the system's frequency response?

3.2.3 Related Publication - Summary

These challenges and questions stated above are addressed in the following publication:

Publication D: ICT based performance evaluation of primary frequency control support and coordination from ReGen plants in smart grids.

As the name implies, this paper evaluates the impact of communication on the provision of frequency control support from ReGen plants, specifically focusing WPPs – contributing the largest share in renewable dominant power systems. The assessment is based on an aggregated WPP model, integrated into a generic power system model that was specifically developed in [5] to assess the ancillary services from power plants. Different test scenarios with two distinct operating conditions of WPP at 50% WP penetration level along with the communication scenarios are taken into account to evaluate the performance of power system frequency response. According to the results in publication [D], in normal conditions, public networks support the provision of frequency control support from ReGen, however, higher communication delays are more prone to affect the overall system's frequency response. Thus, the results in Publication [D] reveal that the design and tuning methodology for frequency/active power control support from ReGen plants must account for the ICT properties (such as communication delay) especially when considering public networks. These results contribute to provide guidelines for the TSOs related to the ICT based issues in the provision of frequency control support from a large number of ReGen plants in future power grid.

3.2.4 Frequency/Active Power Control Coordination from ReGen — Main Results

In order to demonstrate the impact of communication in the provision of frequency/active power control coordination from ReGen plants different test cases were taken in account in Publication [D]. Using the delay traces (for TCP) shown in Figure 3.5, it has been ascertained in Publication [D] that there was no significant impact on the system frequency as compared to the reference scenario (i.e. without communication delay). However, due to network congestion, failure in the communication system or even cyberattacks, the latency in communication may increase up from minutes to even several hours. Thus, for testing the performance of frequency controller at higher latencies in communication, four test cases were considered i.e. with:

- Normal communication (using delay traces shown in Figure 3.5)
- 100 milli-second delay
- 500 milli-second delay
- 1 second delay

Figure 3.8 shows the results from one of the test scenarios in Publication [D] where maximum wind power generation is connected to the public networks for the exchange of messages related to frequency control. Figure 3.8 shows results in terms of system frequency response under different delay conditions compared to the reference frequency response at two different loads i.e. partial load and full load (For details, see Publication [D]).

From Figure 3.8, it can be observed that frequency nadir (i.e. the minimum point reached by the frequency after disturbance) continuously decreases with increasing latency in communication. Furthermore, frequency nadir is seen to have reached to the load shedding limit at a delay of 1 second. Thus, it can be remarked that in case of disturbance in the power system, communication delays have large impact on the overall system frequency response.

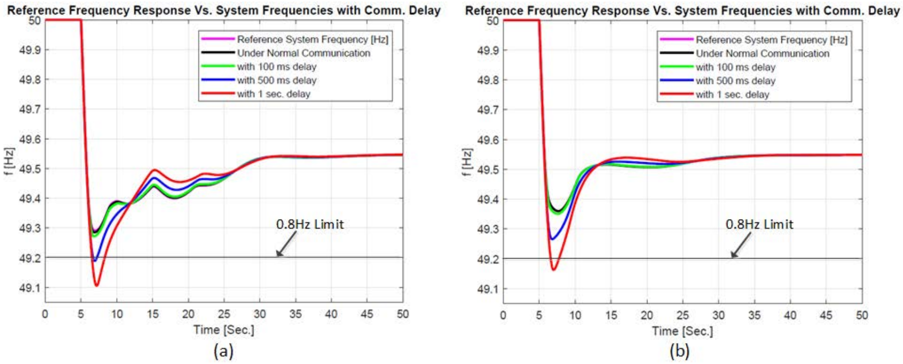

Fig. 3.8: Figure showing two main results from Frequency Control Coordination from WPP in terms of System Frequency Response under different delay conditions compared to the Reference Frequency Response at **(a)** Partial Load and **(b)** Full Load.

3.3 Information Quality Estimation

This chapter presents a separate yet highly relevant aspect related to SG communication in general and specifically for communication requirements related to the provision of ancillary services from ReGen plants i.e. network support for network control systems (NCS). This means that besides looking into the adaption at the controller side, if the communication network is considered to be an active resource offering QoS provisioning or network reconfiguration it is worth investigating how such adaptations can be done and used as additional measures for improving control performance in case of higher network delays or higher packet loss rates. Moreover, this chapter describes related work and the concept of the information quality metric, so-called the *mismatch probability* used in this part of the thesis. This background knowledge should facilitate in understanding the included publications.

3.3.1 Background

There are several challenges with increasing penetration of ReGen plants in the power grid, such as:

1. Energy produced by WPP or PVP is not always available when needed, i.e. WPP depends on wind for energy generation, while PVP on sunlight.
2. RES usually means more distributed power generation, for which the current power grid is not designed to handle (see Section 1). In case of distributed generation, a reverse power flow is observed i.e., from the

LV grid to the MV grid and even the high voltage (HV) grid that leads to problems for grid units such as transform stations [17].

3. The existing grid balancing algorithms are designed for a hierarchical structure, while SG inclines more towards distributed power generation structures (at least within each part of the grid) [17].

Addressing such challenges require exchange of information between many of the entities in SG, whether it is to control voltage, frequency, do power balancing or even make a distributed control strategy etc. This consequently leads to the need for a communication network infrastructure, which allows the exchange of required information. Furthermore, to meet challenges faced by future SGs, power engineers will require to work in close collaboration with control as well as communication engineers. Similarly, while designing the communication strategies and networks for SGs, the communication engineers will have to consider the entities being controlled along with the related controllers. This is for the reason that there are significant difference in, for instance, communication and electrical related equipment, such as in messaging protocols, information models, reliability requirements, temporal consistency, hierarchy etc.) [18]. Secondly, different controllers will be dealing with diverse information, each with a specific timing requirement.

Moreover, implementing communication networks in SGs has several concerns that should be effectively addressed. The main challenge to operate SG over public networks lies in the fact that the network performance may vary according to network utilization. Thus, imperfections in the network may affect the efficiency of control algorithms or even negatively influence the power system. The major imperfections to degrade network performance are network delays and packet/message losses. Secondly, the communication network should be made sufficiently secure to ensure that the information/data is not altered or accessible by intruders. In addition, since such networks will be in charge of connecting the critical infrastructure, a reliable data transmission/reception should be guaranteed. Here, one of the ways to ensure reliability in SG communication networks could be provided preferably with a backup network in case the main network fails to operate or experience temporary faults. However, via the publications [E], [F] and [G], this dissertation contributes by identifying an important aspect in achieving higher information reliability for SG communication networks during normal operation. In the following, the proposed concept along with the summary of individual publication is presented.

It has been ascertained in [E], [F] and [G] that for a reliable operation of the SG controllers, these controllers will rely on correct and timely reception of information from the entity being controlled. Although there are certain functionalities, such as in smart metering, that are not time critical and require a time interval of around 15 minutes or even less [11]. Yet an increasing trend is to focus on automation of DGs, control of DERs and ReGen plant applications [11] that could potentially require lower latencies and more frequent communication intervals (such as < 1 minute). As a consequence, communication networks and technologies that meet the latency requirements of such applications will have to be selected and deployed. Where, the most prominent option is to deploy technologies that are suited to operational needs and financial capabilities - that most probably result in a mix of different heterogeneous technologies [11]. Publication [F] indicates such communication technologies that could become appropriate candidates for the aforementioned applications.

Nevertheless, in all communication technologies, the transport layer in OSI reference model is primarily responsible for providing end-to-end data transportation service using two well-known protocols, namely Transmission Control Protocol (TCP) and User Datagram Protocol (UDP). Although there are several sub-types of both protocols but the former is generally eminent to provide reliable data transportation, while latter is the best effort service provider. Publication [E] discussed the various characteristics of TCP and UDP in context of reliable delivery of messages. In Publication [E], it has been ascertained that while using TCP as a transport layer protocol, lost packets are retransmitted causing augmented delays in data reception. In control algorithms where the information is highly dynamic and even events (that are to be reported) occur quite fast, can be highly effected with these increased delays. Furthermore, based on the network condition, even several information packets can be dropped/lost until the packet is successfully acknowledged or the retransmission limit is reached [11]. Thus, in networks with a very high packet loss rates, the probability of enough packets being lost, which may lead to a connection drop, cannot also be neglected. It is also important to note that the fact that higher packet drop rates will cause increased delay when using TCP means that the network delay can be long enough to exceed the control loop time. Publication [E] elaborates this problem via message sequence diagrams. In contrast, UDP is simple and has no error correction procedure providing the best effort service. While using UDP, depending on the closed loop interval time, the chances of delay exceeding the close loop time are usually quite small, even with the low throughput networks [11]. This means that the main contributor to decreased control performance with UDP is the information/packet loss rate.

3.3.2 Information Quality Metric – Need and Concept

With the above discussion, it is hard to decide whether TCP provides the required reliability for time critical applications in SG or its counterpart, UDP. Therefore, it will be beneficial to have a quality metric based on which it can be established both theoretically as well as practically that which of the two (and even their other sub-categories) outperforms under imperfect network conditions. Now, since the primary objective of a communication network is to provide nodes (on either side of the network) with the correct information in terms of the most recent one, comparing the information at the two ends using both protocols can really be helpful. This is because, if a node in a network (such as voltage/frequency controller) has to make a decision and send set-points based on values remotely accessed from other nodes (such as sensors sending ReGen plant status information), there is a potential for getting an information mismatch, leading to a wrong decision. If the node receives all correct information, there are no issues; however, if some of the information is delayed or dropped on the way, the node may take decision on old information. There might be a risk that this old information is no longer the true representative of the actual state of the other nodes on the network, degrading the controller's performance. This may endanger the operation of a critical system such as SGs. For this reason, the quality metric called mismatch probability (mmPr) has been used in this dissertation. The concept of mmPr was introduced in [6] and has been extensively used in several research articles by now. For instance, [9–11, 13, 14, 17, 23] are to mention a few.

In [6], the mmPr is defined as, "the probability that information element that is used at the requester does not match the current true value at the remote location". While in [14], mmPr is defined as, "the probability of information being inaccurate at some critical point in time where it is used for actuation". The pertinence of using mmPr as a quality metric also comes from the fact that it is based on classical metrics such as network delays along with the impact of access method to information and put those in relation to the dynamics of the power grid scenario. Moreover, the resulting mmPr is presented in the form of a single scaler value that in other cases can be quite complex and not very intuitive.

3.3.3 Related Publications – Summary

Publication E: Impact of transport layer protocols on reliable information access in smart grids.

This publication investigates how the selection of transport layer protocols effects the quality of received information by using mmPr as an information quality metric. It has also been shown in this publication that the selection of UDP or TCP is fundamentally a trade-off between either making the network delay tolerant or information loss tolerant. Using a simple yet relevant network scenario with a proactive-periodic controller, the trends in mmPr for both TCP and UDP are shown, from which it has been concluded that UDP should be preferred for time critical message transmissions, while the standard TCP model assessed is most suitable for non-dynamic and slow changing information type in a smart grid scenario. Moreover, based on the theoretical models for mmPr, this publication illustrates that there is room to adapt TCP e.g. by adjusting timeout values to achieve better performance. Publication [E] contributes to form basis for improvement/optimization of IEC standards that defines requirements for communications in a substation using TCP as a standard for all types of information.

Publication F: ICT requirements and challenges for provision of grid services from renewable generation plants.

As an extension of Publication [E], this article characterizes and presents the control and communication network architectures, performance requirements and research challenges for integrating ReGen plants in the current power grid. As a continuation of the series of Publications [A], [B], [C], [D] and [E], this paper contributes to summarizes the current research status on control and communication network architecture in the next generation power systems with huge penetration of renewable power plants by putting forth some questions and directions for future research. Addressing these questions will really be helpful before a final ICT infrastructure is deployed for the future resilient smart energy system.

Publication G: Information reliability in smart grid scenario over imperfect communication networks using IEC-61850 MMS.

Publication [G] formed the basis of the idea and concept behind Publication [E] and [F]. This publication establishes via Markov chain a simulation-based model for IEC-61850 MMS with the purpose of assessing reliable power balancing in the MV microgrid, over different communication technologies. Publication [G] principally contributes to understanding the behavior of mmPr with the injection of MMS (Manufacturing Message Specification) traffic over TCP and UDP across simulated communication network. The communication network tested with different network delays had significant impact on mmPr, by which it was revealed that not only mmPr increases with the increasing network delays but it also degrades the designed controller's performance. It has also been ascertained in Publication [G] that mmPr is potentially a useful intermediate metric to adjust network access parameters without prior knowledge of the controller implementation. Thus, Publication [G] contributes by opening doors for future research to focus on improving mmPr that leads to an improvement of control performance.

3.3.4 Information Quality Estimation — Main Results

The impact of packet loss and delays in the reception of critical information vary from application to application. The analysis in Publication [E] and [F] is based on the information quality metric mmPr that is used to present trade-off between TCP and UDP or more generally, the trade-off between adding delay for retransmission versus allowing packet losses. Figure 3.9 illustrates the main outcome of the aforementioned publications in terms of a trade-off between packet loss probability and mean delay it takes to achieve same level of mismatch probability for a proactive, periodic update approach. For a given packet loss probability, UDP leads to an effective reduction of update rate, which ultimately reduces the mmPr. If for the same packet loss probability, TCP is used (where the packet loss is reduced to zero through retransmissions), the plots in Figure 3.9 show the mean delay that TCP should attain if the same mmPr should be achieved. If, for a given packet loss percentage, e.g. 0.5%, a TCP connection or any retransmission based scheme would need more than approximately 6.12 seconds if the rate is approximately one event per 10 seconds, then according to the mmPr analysis, a better result will be obtained using a UDP connection. If the event process is varied to, for instance, 1 event per second in average, the delay limit becomes even lower for TCP before a UDP like protocol is preferable, here in the order of 0.5 second end-to-end delay. It has also been ascertained in Publication [F] that these results also depends on the time interval between updates, therefore Figure 3.9 will change if another update rate is chosen.

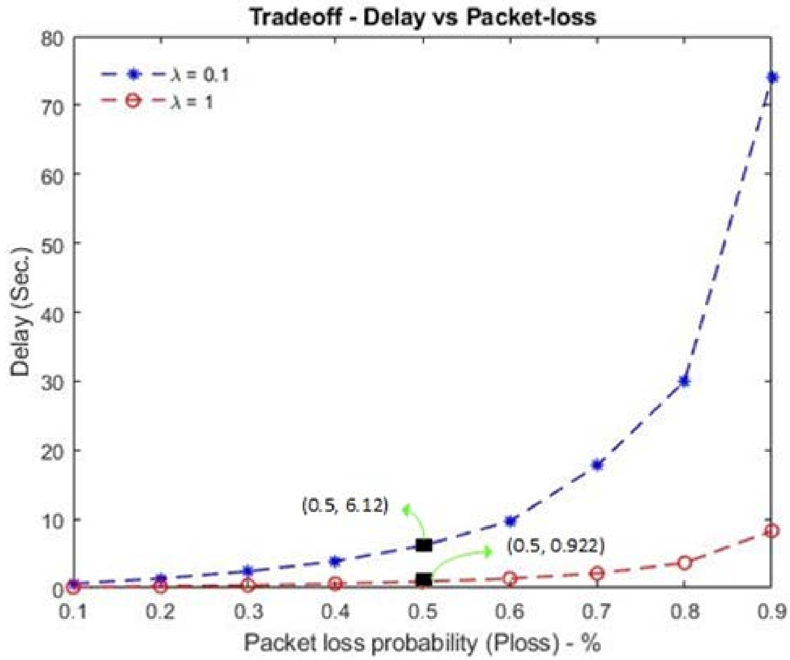

Fig. 3.9: Figure showing main results from Information Quality Estimation that presents tradeoff lines between packet-loss and end-to-end delay for a given propagation delay at two different event rates. The lines show where UDP performs as good as TCP.

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Chapter 4

Conclusion and Outlook

This dissertation mainly aimed to assert the hypothesis that: *General-purpose networks and their related protocol stacks under challenging conditions can really support the provision of AS from ReGen, if properly configured*.

There are two parts of this hypothesis. The first part i.e. "*General-purpose networks and their related protocol stacks under challenging conditions can really support the provision of AS from ReGen*" lead to assess the impact of using general-purpose cellular network communication in providing coordinated voltage/reactive-power as well as frequency/active-power stability support from ReGen plants. In order to assess the impact of cellular network communication on the provision of the selected ancillary services, two QoS parameters were mainly considered, i.e. delay and loss of information. This is because these two parameters cover the impact caused by a wide variety of other QoS parameters, such as throughput etc. Further, with the aim of testing and implementing cellular networks, a Simulink based network simulator was developed to support pattern based network emulation. The patterns that could mimic the intended communication networks and technologies was based on the performance data (comprising traces of end-to-end delay, packet loss etc.) from a Danish cellular network operator. The evaluation results have shown that current cellular networks in normal conditions show satisfactory control performance. However, network imperfections (such as delay or message loss), network faults, congestions and even cyberattacks can highly degrade the control performance, which in case of voltage control coordination were shown as increased power losses, while in frequency control lead to load shedding limit. Thus, these communication network aspects have to be dealt before the final implementation and roll out of controllers responsible for the provision of ancillary services from ReGen plants.

The second part of the hypothesis i.e. "*if properly configured*", lead to explore if the selected information quality metric could be linked to the provision of AS from ReGen and if it could somehow be used to find out a tradeoff between delay and probability of information loss to increase communication reliability. Thus, by considering the communication network to be an active resource offering the provisioning of QoS as well as network reconfiguration, mmPr proved highly beneficial as an indicator of information quality. Furthermore, it was investigated how mmPr can be used as additional measures for improving control performance in case of higher network delays and higher packet loss rates. The overall assessment done in this dissertation provides insights for the smart grid stakeholders regarding the importance and characteristics of ICT related aspects/issues that must be considered effectively during the design and assessment of any ancillary service from ReGen plants in future power systems. Additionally, this dissertation contributes to provide directions for improvement/optimization of IEC based standards that define requirements for communication between electrical substations and control centers.

Beyond the contributions made in this work, several interesting topics and questions arise which could be interesting to explore as a future work. For instance, as indicated in Publication [F], TCP protocol is widely used as a standard in IEC-61850 and other such SG based standards for transfer of data, however, it was not particularly suited for networked control. Designing new transport layer protocols or modifying the already available protocols to meet SG real-time application requirements and then evaluating control performance in comparison to standard protocols could be an interesting topic for further investigation. Similarly, employing the concept presented in publication [E] and [F] regarding the tradeoff between mean delay and packet loss probability to achieve same level of mmPr for TCP and UDP, for network adaptation in SG control applications could be another topic for future research. This would mean to develop an algorithm that may adapt the required protocol functionality based on network conditions.

Part II

Publications

Paper A

On the Impact of using Public Network Communication Infrastructure for Voltage Control Coordination in Smart Grid Scenario

Kamal Shahid, Lennart Petersen, Rasmus Løvenstein Olsen and Florin Iov

The paper has been published in the
SmartGift 2017 – 2nd EAI International Conference on Smart Grid Inspired Future Technologies, 2017.

Abstract

The high penetration of renewable generation (ReGen) plants in the electric supply necessitates online voltage control support and coordination of ReGen plants in the distribution grid. This imposes a high responsibility on the communication network infrastructure in order to ensure a resilient voltage controlled distribution system. A cost effective way to connect the ReGen plants to the control center is to consider the existing public network infrastructure. This paper, therefore, illustrates the impact of using the existing public network communication infrastructure for online voltage control support and coordination of ReGen plants in medium voltage distribution systems. Further, by using an exemplary benchmark grid area in Denmark as a base case that includes flexible ReGen plants, we introduce several test cases and evaluate network performance in terms of latencies in the signals being exchanged between ReGen plants and the control center.

A.1 Introduction

The Danish Government has a target to use 50% of renewable energy by the end of 2020, while making this to be a 100% by 2050. This goal is anticipated to be accomplished by a large scale integration of wind power plants (WPPs) and solar photo-voltaic plants (PVPs) in the medium voltage (MV) distribution system. The high penetration of these ReGen plants into the distribution systems may cause a reverse power flow and depending on the amount of generation and consumption, this will lead to rise in voltage levels. In order to deal with such problems, there are several solutions proposed, for instance, reactive power control using capacitor banks and inductors [8], on-load tap changer (OLTC) transformers at substations [6] and advanced power electronic devices based solutions for voltage control [17]. These solutions either have issues with the power quality, cause a huge percentage of failures or are too expensive for a large scale deployment. However, a simple solution proposed in [18] is the provision of reactive power support from the existing ReGen plants in the distribution grid. This will not only make it possible to down-regulate the entire voltage profile in the distribution system, but also keep the voltage within the limits at the given nodes.

Grids connection requirements for ReGen plants also necessitate the provision of reactive power support, which is offered by today's ReGen plants. However, this capability is not utilized by Distribution System Operators (DSOs), mainly due to the lack of technical infrastructure to communicate and control these units. The DSOs in Denmark have already started to install and deploy SCADA systems [3], but, controlling the ReGen plants may not be feasible in long term due to lack of regulatory framework. It is foreseen that aggregators of these ReGen units may take the responsibility, in close cooperation with local DSOs, for hosting voltage control capabilities besides the energy trading. An ancillary market for the provision of voltage/reactive power provision is also expected in the near future [10]. Thus, the needs for coordination in providing reactive power support and hence controlling voltage locally on a distribution grid is required in respect of the increasing number of dispersed units. This service may be provided by the same aggregators which nowadays are trading renewable energy or may be in the responsibility of the DSOs. Therefore, at this stage, we consider that it is the Aggregator control unit that is responsible for providing reactive power support and controls the voltage locally on the distribution grid.

Nevertheless, the coordination between ReGen plants and the Aggregator imposes high responsibility on the ICT infrastructure. Although implementing a reliable, high speed connection, e.g. fiber optics, to all ReGen plants in the grid seems the best possible option, but this being very expensive considering the huge penetration of ReGen plants, is not feasible. There exist several other options too, as detailed in [13, 21], but the idea is to use an already existing infrastructure that offers low operating costs, faster deployment, high speeds, flexibility and provide full expertise and manning to operate the network. Nowadays, cellular networks (e.g. UMTS, LTE) are already widely deployed by the telecom operators in Europe with high coverage [5]. Therefore, this paper focuses on the use of the existing cellular network communication infrastructure, e.g. owned by Tele Denmark Communication (TDC), as a base case and outline its impact on the online voltage control and coordination functionalities for ReGen plants in distributed grids. The outcome of this study serves as a generic guidance on the use of existing public network infrastructure to coordinate the voltage-stability support capabilities of ReGen plants in a distribution system with large ReGen penetration in order to ensure a resilient voltage controlled distribution system.

The control of power systems over cellular networks has been addressed in several papers. In [14] and [9], the authors focus on the latency requirements of delay-critical operations in medium voltage grid. They perform an assessment of latency and reliability for LTE technology under various load conditions. The work is based on conducted field trials using IEC-61850 standard. The authors conclude that LTE, in general, fulfills delay and reliability requirements of medium voltage grid applications. However, the authors in [14] and [9] do not focus on the voltage control coordination in particular considering the high penetration of ReGen plants in the power grid. Reference [11] provides a comprehensive survey investigating the challenges and propose architectural and protocol improvements of cellular technology to support NAN applications in a smart grid scenario. The authors propose a redesign of current LTE cellular networks to enable autonomous and automatic interactions for smart energy systems, with emphasis on enabling mission-critical applications.

The remainder of this paper is organized as follows: Section A.2 explains the voltage control coordination scenario in power distribution systems, highlighting several ways and challenges to connect ReGen plants to the Aggregator control unit. The challenges related to the online voltage control coordination in the MV grid are outlined by exemplary test cases in Section A.3. In Section A.4, time domain analysis is performed to test the impact of using public network infrastructure for online voltage control coordination. The conclusion of this study and future work is given in Section A.5.

A.2 Power System and ICT Challenges

A.2.1 Voltage Control Coordination in Power Distribution Systems

One of the challenges in power systems is to keep the voltage profile within the desired tolerance band margins, stipulated by the so-called Grid Code requirements that need to be fulfilled by any generation unit being connected to the power system. In MV distribution grids the voltage has to remain within ±10% of its nominal value [2]. If these limits are violated at certain points within the grid, affected generation and consumption units need to be disconnected, which can eventually lead to severe stability problems in the entire power system. One way for a single ReGen plant to contribute to voltage regulation is realized by a local voltage controller as shown in Figure A.1.

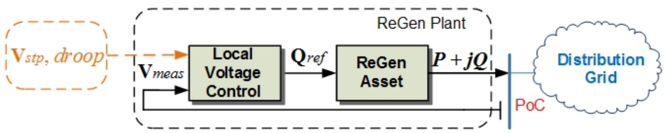

Fig. A.1: Voltage control scheme of ReGen plant [4]

The ReGen plant has an inner control loop for regulating reactive power provision at the Point of Connection (PoC) and an outer voltage control loop for controlling the voltage in the PoC. A typical droop function is to be configured for the ReGen plant controller, i.e. a voltage reference point V_{stp} and a droop value needs to be specified. It has been ascertained in [18] that it is sufficient to introduce these settings once as an off-line initial system analysis in order to achieve satisfactory voltage regulation within the tolerance band margins.

However, there can be other control objectives imposed by the DSO, e.g. to reduce the grid power losses which are caused by reactive power provision. This can be achieved by optimizing the control settings in a so-called distributed on-line coordination scheme [19]. Since the power output of ReGen plants varies continuously and thereby the voltages in the distribution grid, an Aggregator of grid support services may take over the task to update the controller settings of the ReGen plants continuously in real-time according to the actual operating point.

The involved actors of such coordination scheme are illustrated by means of Figure A.2. The DSO needs to provide the system parameters of the distribution grid. The Aggregator receives measurement signals of voltage, active and reactive power (V_{meas},P_{meas}, Q_{meas}) as well as the available reactive power (Q_{ava}) from all ReGen plants (1...N) and dispatches the droop settings (V_{stp}, $droop$) for the voltage controllers. In this study, an MV distribution grid in the Northern Denmark is used as benchmark test model. It represents a typical radial feeder topology with primary substation (60/20 kV) and four ReGen plants (WPP, PVP 1, PVP 2 and PVP 3), accounting for realistic penetration of renewables in Danish distribution grids in the future (see [18] for more details of the benchmark grid model).

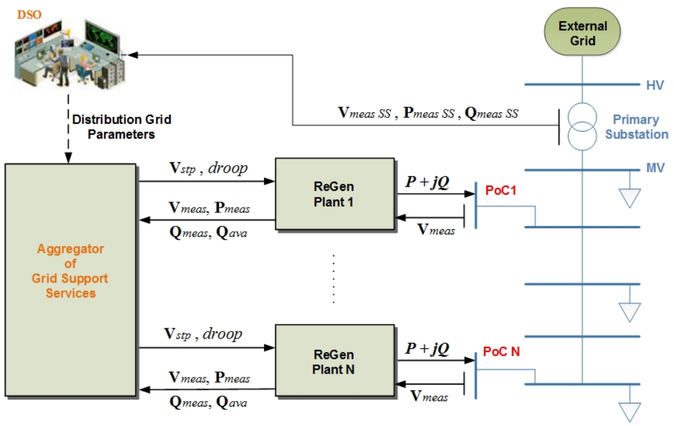

Fig. A.2: Scheme for Distributed On-Line Coordination of voltage control functionalities

A.2.2 Communication Network Infrastructure

In order for a ReGen plant to have online coordination with an Aggregator control unit, it should be connected to the Internet via some Internet Service Provider (ISP). This lets the ReGen plant to exchange information with all of the other accessible controllers/ReGen plants on the Internet. Since here as a base case we are considering the public mobile networks as ISPs, there are, therefore, a number of ISPs available. The ISP used by the ReGen plants can, thus, be different with that used by the Aggregator. The ISPs are usually distinguished by the amount of bandwidth they provide, the service cost and most importantly, the connectivity.

An ISP network consists of long distance transmission lines that interconnect routers at Point-of-Presence (POP) in different cities that the ISPs serve. This equipment is called the backbone of the ISP. If an information packet is destined for a device directly served by the ISP, it is routed over the backbone and delivered to that device. Otherwise, it must be handed over to another ISP [12]. The ISPs are connected to rest of the Internet through Internet eXchange Points (IXP) and exchange information [1]. Thus, for devices on different networks to communicate, the communication traffic needs to go through an IXP, even though the devices are physically right next to each other. These ISPs are said to peer with each other, having a bilateral agreement [1] for the provision of a certain service level. Therefore, in the existing implementation, this change of ISP networks will not have significant effect and the delay may increase up to a few tens of milli-seconds (ranging between 10 – 50 ms above the normal delay) [15].

Furthermore, in the given benchmark grid scenario (see Section A.2), the Aggregator control unit can be placed at the local primary substation or anywhere else in Denmark. The distance between ReGen plants and the Aggregator, however, can be one of the external influences on latency as well as other communication properties described in [16]. The voltage control information being time critical can, therefore, be effected by the time the signal takes to go from a ReGen plant to the aggregator and a set-point/reference signal from Aggregator to the ReGen plant. Since the ISPs are deploying faster network technologies [15], e.g. 3G, LTE/4G and HSPA+ etc., this enables higher data transfer rates and quality of service for the network users, and makes the users accustomed to have high speed networks and capable devices. Still, for the heterogeneous networks that are usually shared by a large number of users and data exchange is exposed to stochastic non-controllable delays and packet drops, extra delays can be expected in long distance communication.

A.2.3 Communication Network Model

In order to get a realistic and accurate model of the network behavior within the benchmark grid area, a system called NetMap [15] is used. NetMap is a mobile-network performance measurement system based on crowd sourcing, which utilizes end user smart devices to automatically measure and gather network performance metrics on mobile networks. The measured metrics include throughput, round trip times, connectivity, and signal strength, accompanied by a wide range of context information about the device state [15]. It offers a Network Performance Map (NPM) based on actual measurements on existing networks using actual end user devices in real end user scenarios. The NPM shows what network performance to expect and provides a more realistic image of what the end system can expect as the measurements are performed with similar devices [15]. According to the NMP in [15], the throughput provided by the existing public network infrastructure is sufficient enough to support voltage control coordination in the said scenario. Therefore, in this paper we base our analysis on the latency a signal might incur while going from the ReGen plants to the aggregator controller (and vice versa) and other connectivity related issues to see the impact on the performance of voltage controller.

NetMap gives the measure of latency in the form of Round Trip Times (RTT) measured using a large number of end devices located at different distances from the Aggregator control unit. Figure A.3 shows the real time RTT measurements based on around 3500 TCP-RTT measurement sequences at different distances/locations of the end devices from the Aggregator control unit using different ISPs. These measurements have been obtained over a period of one and a half year with varying number of end devices. It can be observed in Figure A.3 that for the maximum cases, RTT lies within the range of 30 ms approximately, which means that a minimum of 15 ms delay (half of RTT – assuming the same route for request and reply to/from the server) in the transfer of information update can be expected for the maximum times in daily operations. We, therefore, take this as a normal base case for our future evaluation. However, this network being heterogeneous (and shared by a large number of users), the delay may increase depending on the network conditions. In the worst case, this delay may jump up to 500 ms (RTT), as seen in Figure A.3.

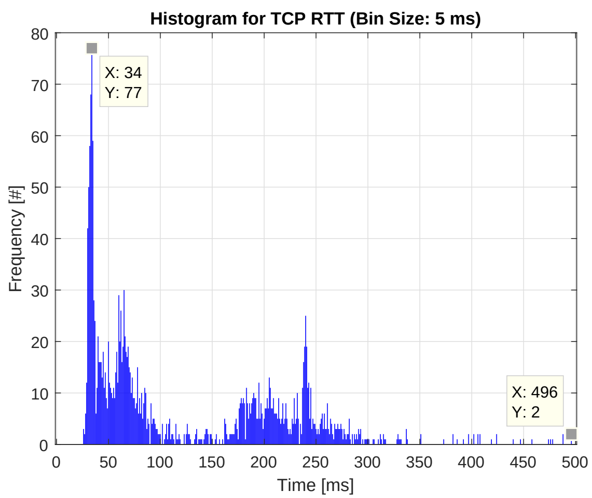

Fig. A.3: Distribution of TCP RTT measured around the benchmark region

A.3 Link Layer Failure

In public wireless communication networks, despite of having several communication masts (base-station) nearby, the ReGen plant usually connects to the nearest communication mast having the strongest signals. While associated with a mast, a plant controller periodically measures the strength of a beacon signal from its nearest mast as well as beacon signals from nearby communication masts that it can hear. These measurements are reported once or twice a second to the controller′s current mast [12]. A handoff occurs when an aggregator controller changes its association from one communication mast to another while communicating with any ReGen plant controller.

The handoff occurs due to several reasons, for instance: **a)** current communication mast fails to operate, **b)** the signal between current communication mast and the plant controller deteriorate to such an extent that the connection between a ReGen plant controller and the aggregator controller is in danger of being dropped or **c)** cell becomes overloaded, handling a large number of users [20]. This situation can be dealt by handing off the connected stations to less congested nearby cells. It is worth mentioning that a handoff between masts results not only in the controller transmitting/receiving to/from a new mast, but also in the rerouting of the ongoing communication from a switching point within the network to the new mast. All this would ultimately add to the delays in sending update information from a ReGen plant controller to the aggregator control unit and set-points from Aggregator to ReGen plants.

Therefore, we consider here a test case where, for instance, the radio connection of a plant controller with its base station (cell) suddenly fails. This failure can be due to equipment failure, radio link failure or any other problem within the base station. During such failures, there exist two possibilities: **a)** the area is covered by other cells or **b)** the area is not covered by other cells.

A.3.1 The area is covered by other cells:

The end system detects that there is a problem at the physical layer, when it is out of synchronization for a certain number of consecutive times defined in a parameter set by ISP [7]. A common value of this parameter is 20 times [7]. After detecting a physical layer problem, the user equipment (UE) starts a timer configured by ISP (a typical value is 2 seconds. [7]). If it recovers synchronization with the serving cell, it resets the timer and everything continues as it was (the recovery was possible). However, if it does not succeed, UE initiates the whole process, look for a suitable cell, connection setup and so on. Putting in nutshell, the whole process may take few seconds to minutes, depending on the severity of the problem.

A.3.2 The area is not covered by other cells:

In such a case, the service remains disrupted until the same mast is fixed or communication link is recovered. The delay in service outages may vary from few minutes to hours depending upon the type of problem incurred. While considering the worst cases, it is worth mentioning a problem seen a couple of years back in Norway at part state-owned telecoms firm Telenor that left around 3 million users without coverage for up to 18 hours, caused by a signal storm [4]. Although rare, but such outages must also be considered when targeting to design resilient communication systems.

From the above discussion and the test-cases defined, it can be remarked that the network architecture/setup can introduce signal delays in the range of milli-second to seconds, while failures in communication may impose latencies in the range of minutes up to hours, depending on how severe the failure is. Table A.1 summarizes the latencies in communication, resulting from all considered test cases.

Table A.1: Resulting performance metrics for test cases.

Test Cases	Category	Latency (RTT)
Base Case	Normal	30-50 ms
	Worst	500 ms
Link Layer Failure	Normal	Seconds to few Minutes
	Worst	Minutes to Several Hours

A.4 Assessment of Voltage Control Coordination

As mentioned in section A.2, distributed voltage control can increase the power losses in the grid due to reactive power loadings of the lines. The total power losses occurring in the cables/lines are evaluated based on the total active power generation by the ReGen plants in a certain distribution grid, as given in A.1:

$$P_{(loss,tot,\%)} = P_{(loss,tot)} * 100\% = \frac{(\sum P_{loss})}{\sum P_{gen}} * 100\% \tag{A.1}$$

According to [19], continuously updating the voltage set-points (see Figure A.2) for the ReGen plants is the only effective option to improve the proposed distributed control concept with regard to the power losses within the grid. The idea behind this control concept is that nominal voltage with $V_{stp} = 1pu$ does not necessarily have to be targeted, as long as the voltage remains within the tolerance band margins of $\pm 10\%$. Thus, as long as the measured voltage does not exceed a certain critical point, the voltage set-point can be enhanced to avoid unnecessary reactive power support, hence avoiding additional power losses. In this context, the update rate of the voltage set-point will have an impact on the average power losses over a certain time period. A more detailed description of this control concept will be given in a separate publication.

A.4.1 Impact of Latency

The latencies introduced by the communication network lead to delays of measurement signals being sent from the ReGen plants to the Aggregator as well as delays of reference signals being set from the Aggregator to the ReGen plants. The results obtained in [14] show that, for adjusting the voltage set-point, various update rates in the range of seconds to minutes have a minor impact on the resulting power losses within the grid. Hence, with regard to the obtained latencies for the test cases in the communication network (Table A.1), it can be remarked that RTTs in the time range of seconds to minutes would not affect the control performance significantly. As, for instance, if the maximum signal delay in worst case reaches to 500 ms (Figure A.3) is negligible, assuming that the update rate of the voltage set-point is minimum 10 seconds.

A.4.2 Impact of Link Failures

Even if a communication failure in the network sustains for several minutes, the local voltage controller of the ReGen plant will apply the last sent set-point, which results in negligible deviations in the power losses in the distribution feeder. However, as revealed in Section A.3, under certain circumstances connection failures up to several hours can occur which may affect the power losses more significantly. These communication problems can be due to a failing communication mast without having any available back-up cell. For this, taking into account different test cases, we evaluate the extent to which the latencies in communication up to several hours will affect the on-line coordination of voltage control functionalities in distribution grids.

Test Cases. For testing long-lasting communication failures, a benchmark test scenario with a time frame of 24 hour is applied [14]. Four test cases are considered in terms of hours of delay caused due to communication failure i.e. 1 h, 6 h, 12 h and 24 h.

Test Results and Analysis. Figure A.4 shows the line losses expressed as percentage of the total generated power by all ReGen plants, averaged over the simulation period of 24 hours, with and without various communication failures. It can be observed in Figure A.4 that the power losses increase for longer communication failures. The blue-colored bars show the power losses without any voltage control. However, in this case the tolerance band margins of the voltage (±10%) are not fulfilled. Then, voltage regulation with maintained settings for the ReGen plant controllers (off-line, red-colored) leads to a considerable increase of the power losses. By introducing distributed on-line coordination (no fail., green-colored), the losses can be reduced to a significant extent. However, the power losses increase depending on the duration of the communication failure in the system.

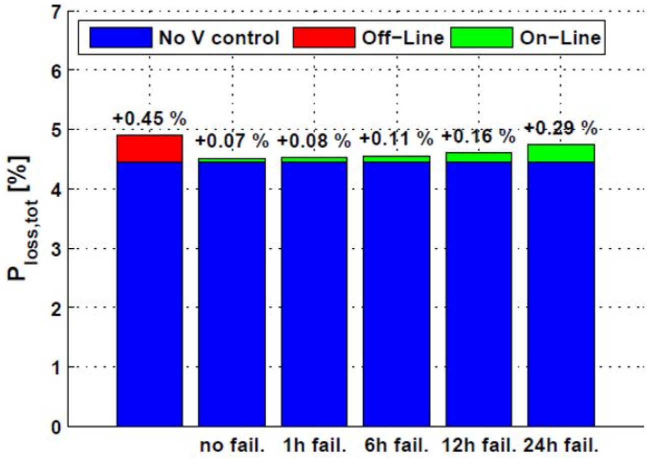

Fig. A.4: Average power losses over the simulation period for various durations of communication failure for updating the voltage set-points.

An exemplary voltage profile for a communication failure persisting for 12 hours is depicted in Figure A.5. The resulting depression of the voltage profile between 6:00 a.m. and 6:00 p.m. is not required as the voltages are sufficiently below the upper limit of 1.1pu, implicating an undesirable rise in the power losses. After occurrence of the failure at 6:20 a.m., the last sent voltage set-point will be applied during the faulty period. This results in significant reactive power provision, since the voltage set-point is not anymore updated according to the voltage measurements, hence increasing the power losses in the system.

A.5 Conclusion

This paper elaborates on the impact of communication on on-line voltage control coordination in distribution grids using existing public network communication infrastructure. The use of public network communication in-

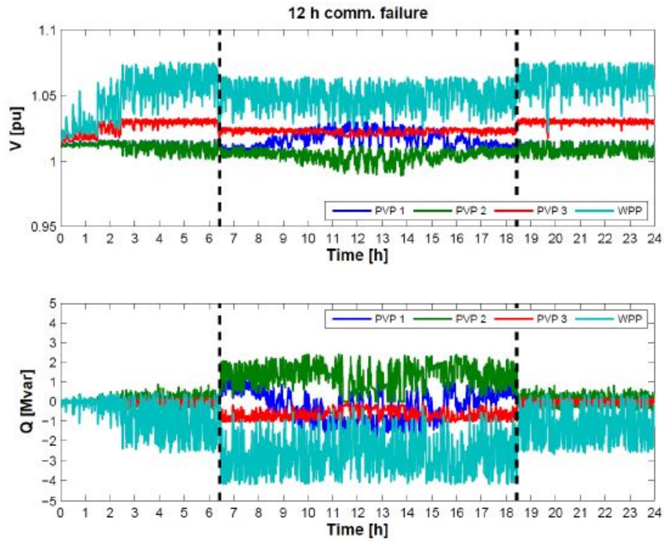

Fig. A.5: Voltages of all ReGen plants over one day for a communication failure occurring between 6:00 a.m. and 6:00 p.m.

frastructure has various aspects associated to it that may result in deviating voltage control performance in the distribution grid. Although, the throughput offered by these networks is suitable enough to support voltage control coordination; but, being used by a number of users at the same time, unexpected/unwanted delays in information exchange may incur. Therefore, several test cases are introduced and evaluated with respect to the related latencies and validity of the signals being exchanged between Aggregator and ReGen plants. According to the results, delays in communication in the range of seconds to minutes have a minor impact on the resulting power losses. However, the delays up to several hours may lead to higher power losses in the grid, increasing the cost of energy which is eventually recovered by the end-consumers of electricity.

In this paper, we only focus on the use of existing public network infrastructure, which leads to the direction of studies in future. For instance, cost estimation to employ these cellular networks for voltage control coordination and then comparing it to the cost of employing other communication networks, such as cable networks. Secondly, securing networks when used in critical infrastructures is crucial. Therefore, the impact of adding security to the information exchange on the controller's performance will also be explored as a next step.

Acknowledgment

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Paper B

On the Impact of Cyberattacks on Voltage Control Coordination by ReGen Plants in Smart Grids

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Lennart Petersen and Florin Iov

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Abstract

Wind power and Solar photovoltaic plants are expected to jointly produce a lion(s) share of renewable energy generation capacity needed to reach the target of having green energy around the globe. In this respect, investigation of voltage stability support and coordinated control are crucial step stones towards a future resilient power system. The ability to provide online voltage stability support from Renewable Generation plants highly depends on the communication infrastructure that allows an exchange of information between different grid assets. Any attempt to attack this communication system can lead to an unstable grid and in worst case, a complete blackout. Therefore, this paper illustrates the impact of cyberattacks on the voltage control coordination between the renewable generation plants and the system operator in microgrid settings. More specifically, this work focuses to show how time-varying delays and manipulation of exchanged information caused by cyberattacks can affect the controller performance. Finally, security solutions are proposed that make voltage control coordination resilient against these cyberattacks without adding additional delays to the process.

B.1 Introduction

Today, a large part of the wind power in Denmark, i.e., 3799 MW is coming from onshore wind turbines [12] [1], which are distributed individually or in small scale clusters, while the PV production mainly consists of dispersed residential small units up to 6 kW [16]. The anticipated trend is that the increased share of installed renewable energy in Denmark in the coming years will mainly be accomplished by integrating large concentrations of off-shore WP plants (WPP) in the transmission system, as well as large scale concentrated PV plants (PVP) and new generation onshore WPP in the distribution system [12]. This foreseen high penetration of Renewable Generation (ReGen) plants into the Danish electricity supply may cause several problems, as discussed in [12] and [15]. According to [12], the provision of reactive power support from ReGen plants in the distribution grid will not only make it possible to down-regulate the entire voltage profile in the distribution system, but also keep the voltage within the limits at the given nodes. Thus, the needs for coordination in providing reactive power support and hence controlling voltage locally on a distribution grid is required in respect of the increasing number of dispersed units. It is foreseen that aggregators of these ReGen units may take the responsibility, in close cooperation with local DSOs, for hosting voltage control capabilities besides the trading energy [7]. Therefore, at this stage, we consider that it is the aggregator control unit that is responsible for providing reactive power support and controls the voltage locally on the distribution grid.

It has been ascertained in [15] that the provision of reactive power support from ReGen plants and hence controlling voltage locally on a distribution grid imposes high responsibility on the ICT infrastructure. In [15], the authors have illustrated the use of the existing public network communication infrastructure as a base case and outlined its impact in terms of added latencies due to, for instance, network failures on the online voltage control coordination functionalities for ReGen plants in distributed grids. However, vulnerabilities associated with the use of public communication networks and information systems may be exploited for financial or political motivation to delay, block, alter process related information (with fraudulent information) or even direct cyberattacks against ReGen plants, thereby preventing the aggregator control unit from obtaining production metrics. In any case, this will impact the integrity, confidentiality or availability of the ICT system [4] and, thus, strategies should be defined to cope with such risks. For this reason, as an extension of the work presented in [15], this paper illustrates the impact of time-varying delays and manipulation of the control messages caused by cyberattacks on the system(s) performance. The European Smart Grid Information Security (SGIS) working group [5] is used as a reference for determining the level of security threat to the system.

The security of power systems using cellular networks for control purposes has been addressed in several papers. For instance, in [17], the authors analyze end-to-end security of the communication between DSO substation and distributed energy resources (DERs) over heterogeneous networks through TLS encryption and authentication in compliance with IEC 62351-3. Reference [9] describes an approach to use standardized technologies to provide secure communications for ancillary services with minimal configuration by administrators of corporate networks. The authors in [9] also discuss the problems of integrating legacy devices. However, the authors in [9] do not focus on the voltage control coordination in particular considering the high penetration of ReGen plants in the power grid. Reference [4] focuses on medium voltage grids characterized by a high level penetration of ReGen plants and examines the risks associated to the communication malfunctions of an ICT architecture implementing the voltage control function. Reference [4] is mainly based on the studies related to the Italian medium voltage grid without actually showing the impact of ICT malfunctioning on the grid implementation and voltages due to cyber-attacks. Whereas, in this paper the results are based on a Danish medium voltage (MV) distribution grid located in the Northern Denmark as a benchmark model to show the impact of cyber-attacks in terms of power losses in the system.

The remainder of this paper is organized as follows: Section B.2 explains the voltage control coordination scenario in power distribution systems, highlighting several ways and challenges to connect ReGen plants to the aggregator control unit. The security challenges related to ICT in providing the online voltage control coordination in the MV grid are outlined in Section B.3. Section B.4 provides the impact that cyberattacks have on the online voltage control coordination between ReGen plants and aggregator control unit. While, in Section B.5, solutions are proposed to secure this communication without effecting the control(s) performance. Finally, the conclusion of this study is given in Section B.6.

B.2 Benchmark Grid And System Description

In MV distribution grids, one of the challenges is to keep the voltage within ± 10% of its nominal value [15]. In case these limits are violated at certain points within the grid, affected generation and consumption units need to be disconnected, which can eventually lead to severe stability problems in the entire power system. Figure B.1 shows one of the ways for a single ReGen plant to contribute to voltage regulation, realized by a local voltage controller.

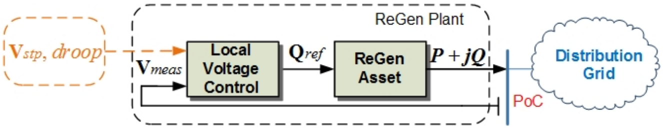

Fig. B.1: Voltage control scheme of ReGen plant [15]

Here, the ReGen plant has an inner control loop for regulating reactive power provision at the Point of Connection (PoC) and an outer voltage control loop for controlling the voltage in the PoC [12] [15]. A voltage reference point (V_{stp}) and a droop value needs to be specified for the ReGen plant controller. The other control objectives imposed by the DSO, e.g. to reduce the grid power losses which are caused by reactive power provision, can be achieved by optimizing the control settings in a so-called distributed on-line coordination scheme [14]. Since the power output of ReGen plants varies continuously and thereby the voltages in the distribution grid, an aggregator of grid support services may take over the task to update the controller settings of the ReGen plants continuously in real-time according to the actual operating point [15].

Figure B.2 illustrates the actors involved in such a coordination scheme. As defined in [12] [15], the DSO needs to provide the system parameters of the distribution grid. The aggregator receives measurement signals of voltage, active and reactive power ($V_{meas}, P_{meas}, Q_{meas}$) as well as the available reactive power (Q_{ava}) from all ReGen plants $(1, ..., N)$ and dispatches the droop settings ($V_{stp}, droop$) for the voltage controllers.

As in [15], to account for a realistic penetration of renewables in the Danish distributed grids in the future, a MV distribution grid in the Northern

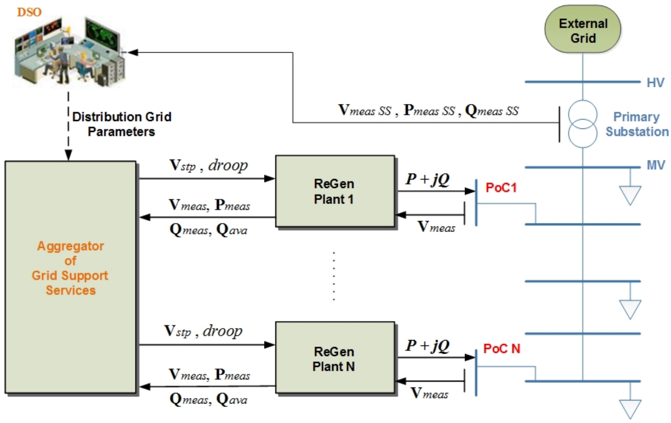

Fig. B.2: Scheme for Distributed On-Line Coordination of voltage control functionalities [15]

Denmark has been used for this study (see Figure B.3). This distribution grid represents a typical radial feeder topology with primary substation (60/20 kV) and four ReGen plants. In Figure B.3, the ReGen plants are shown as WPP, PVP 1, PVP 2 and PVP 3 (the benchmark grid model is presented in detail in [13]). Figure B.3 also shows the connection of all ReGen to the aggregator unit through a communication network. This network is a third party public communication network, as illustrated in [15]. The following section explains different types of cyber security risks associated to the use of these public networks for the online voltage control coordination in the said scenario.

B.3 Security Scenarios in Online Voltage Control Coordination

Security of critical infrastructures is facing many threats, particularly when systems are connected to the internet. In private, isolated networks physical security provides an important layer of security. However on the internet, segregation and firewalling can limit the attack surface, but part of connected systems must be exposed for the internet to be of use and consequently also exposed to attacks.

B.3.1 Cyber-Attacks on ICT

There are several kinds of cyberattacks based on the types of "hackers", as elaborated in [10]. In context of the scenario explained in Section B.2, the sabotage caused by these attacks is considered as reducing/removing the avail-

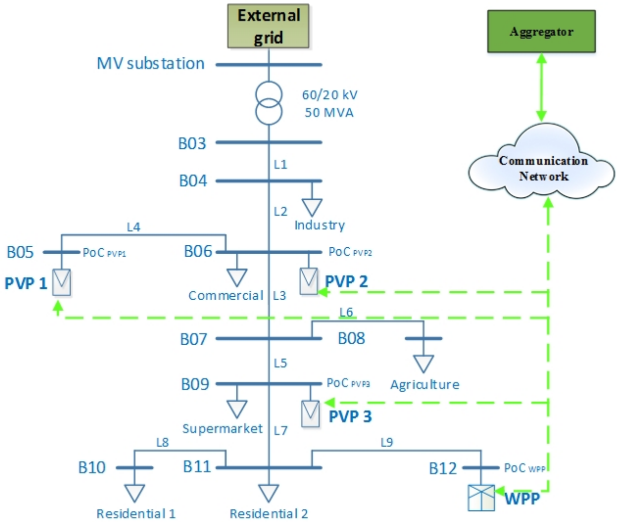

Fig. B.3: Structure of MV benchmark grid showing communication of the aggregator control unit with ReGen plants

ability of online voltage control coordination functionality or manipulation of the droop values. In terms of cyberattacks, reducing/removing the availability of service provided by the infrastructure can be achieved particularly by an interesting type of attacks called Distributed Denial of Service (DDoS). DDoS attacks are not novel or necessarily very sophisticated, but they are cheap, simple and often highly effective in achieving their goal of breaking the availability. Minute long attacks can be bought online as a service for as little as $5, [8]. By remote controlling networks of infected machines, so called botnets, the attackers abuse these distributed platforms to generate devastating amounts of traffic. Volumetric attacks, such as UDP flood, seek to starve network link capacity. Volumetric attacks easily reach hundreds of Gbps, while the recent extreme case of the Mirai botnet suggests that as many as 100,000 bots generated 1.2 Tbps at the peak [2]. Network and application layer attacks aim to exhaust resources (memory, CPU etc.) of either the protocol stack implementation or applications. For these attacks, hundreds of thousands of requests per second are sent to the target, rendering it unable to handle the legitimate traffic. Impacts of DDoS attacks range from no impact if they fail to exhaust the target, over increased packet loss, delay and jitter, to the successful attack, where the targeted service becomes fully disabled.

In contrast to the simple, cheap and readily available DDoS attacks, there are the so-called targeted attacks. A targeted attack involves investment of time from a team of highly trained specialist to tailor the attack. Such effort is costly, but obviously also likely to succeed, given enough resources, and the outcome will typically be complete, covert control, of the targeted systems. In the case of SCADA networks, attack will typically give the attackers full control over some part of the plant. This can be used to perform espionage by exfiltrating data or to interfere with operation of a plant. By tampering with actuation and sensing signals, attackers can disturb production and even cause physical damage. A well-known example of a targeted attack on SCADA systems is the Stuxnet malware. The goal appears to have been to disrupt Iranian uranium processing plants. The attack was carried out over years, it was designed to break mechanical parts very slowly to stay undetected and it relied on agents on the ground to facilitate breaching into isolated networks. Furthermore, the attack exploited multiple zero day vulnerabilities - Software vulnerability which are not known to the public at the time and which are traded on underground markets for tens of thousands of dollars. All this speaks to a large amount of resources being invested in the attack and it has been speculated that nation states are behind, [3]. The point is that in the end an attacker with enough resources appears to be able to compromise and tamper with any ICT. According to [4], voltage control coordination is important because it has a direct influence on both the power operation and economy, and includes a high level of inter-networking requirements for its ICT architecture. Therefore, in the case of aggregator control units communicating with the ReGen plants, the risks involve espionage and sabotage towards any part of the whole power system.

B.3.2 Modeling the Cyberattacks test cases

Following scenarios can be defined to model the real attacks discussed above.

Case 1 Small UDP flood on aggregator control unit. This exemplifies a volumetric DDoS attack of the sort that can be launched with hardly any knowledge and only a few dollars. A 200 Mbps stream of UDP packages, lasting 5 minutes, is sent to the IP address of the aggregator control unit.

Case 2 Large UDP flood on aggregator control unit. Unlike Case 1, the modelled attacker makes use of a botnet and relies on techniques such as amplification and reflection to sustain a 1.2 Gbps DDoS attack for 5 days. This requires a lot more technical knowledge and preparation than Case 1, yet it is still simple compared to a targeted attack. The throughput is set to the estimate of the largest known attack, while the duration reflects the arbitrary choice of the attackers to discontinue the attack. Apparently, this attack seems too long to be realistic and one might think of turning off the server, reset the configuration or even cutting off the communication to prevent further sabotages. However, the DDoS attack may not necessarily just disappear by going offline. It highly depends upon the motivation and anger the attacker has to harm the system. He might wait for the system to get online again.

Case 3 TCP Reset on aggregator control unit. In this targeted attack the attacker have invested many resources and relied on advanced techniques to get access to a real-time copy of the traffic to and from the aggregator control unit, as well as the ability to send forged traffic to the aggregator control unit. The attacker exploits this to transmit forged TCP Reset packets, effectively closing all TCP connections to and from the aggregator control unit. It is assumed that engineers are reacting very promptly and can identify and mitigate the problem after 12 hours.

Case 4 Small UDP flood on ReGen. Same as Case 1, but targeted at a ReGen plant.

Case 5 Large UDP flood on ReGen. Same as Case 2, but targeted at a ReGen plant.

Case 6 TCP Reset on ReGen. Same as Case 3, but targeted at a ReGen plant.

Case 7 Targeted attacker tries to break the power plant physically, for instance, through oscillations or manipulate the droop values. The interesting bits requires understanding of the plant. For instance, what changes will the attacker make to droop values and control signals to cause catastrophic damage to the ReGen plant or the power system?

B.3.3 Summarizing the effects caused by Cyber-Attacks

Based on the few (out of many) cyberattack cases described above, the effects caused by these attacks can be categorized into two types: First, added latencies in sending status updates from ReGen plants to the aggregator control unit or set-points from aggregator to the ReGen plants. Second, false messages sent to/from the aggregator/ReGen. These attacks may become a high risk to the integrity, availability and confidentiality of the whole power system. Therefore, depending on these two cases, we now analyze the impact of different level of latencies and false messages due to cyberattacks on the on-line voltage control coordination and ultimately on the power losses in the following.

B.4 Impact Of Cyber-Attacks on Power System

In [15] and [13], it has been ascertained that for adjusting the voltage set-point, various update rates in the range of seconds to minutes have a minor impact on the resulting power losses within the grid. Therefore, it can be remarked that delays caused by UDP flood attacks or even TCP Reset attacks in the time range of seconds to minutes would not affect the control performance significantly, assuming that the update rate of the voltage set-point is 10 seconds (minimum). Even if the communication between ReGen plants and the aggregator control is disrupted for several minutes, the local voltage controller of the ReGen plant will apply the last sent set-point, which results in negligible deviations in the power losses in the distribution feeder [15].

However, as revealed in Section B.3, cyberattacks can disrupt the connection up to several hours, which may affect the power losses more significantly. For this, taking into account different test cases for communication failure in [15], we have evaluated the extent to which the latencies in communication up to several hours will affect the on-line coordination of voltage control functionalities in distribution grids.

B.4.1 Test Cases for added latencies due to cyberattacks

For testing long-lasting communication failures, a benchmark test scenario with a time frame of 24 h was applied in [15]. Four test cases were considered in terms of hours of delay caused due to communication failure i.e., 1 h, 6 h, 12 h and 24 h.

Figure B.4 shows the line losses expressed as percentage of the total generated power by all ReGen plants, averaged over the simulation period of 24 hours, with and without various communication failures [15]. It can be observed in Figure B.4 that the power losses increase for longer communication failures. The blue-colored bars show the power losses without any voltage control. However, in this case the tolerance band margins of the voltage ($\pm 10\%$) are not fulfilled. Then, voltage regulation with maintained settings for the ReGen plant controllers (off-line, red-colored) leads to a considerable increase of the power losses. By introducing distributed on-line coordination (no fail., green-colored), the losses can be reduced to a significant extent. However, it can be observed from Figure B.4 that the power losses increase depending on the duration of the communication failure in the system.

B.4.2 Manipulation of Droop/Set-point Values due to cyberattacks

In [12] and [15], it has been ascertained that relatively flat droop characteristics of the local voltage controller in the ReGen plants lead to instable voltage

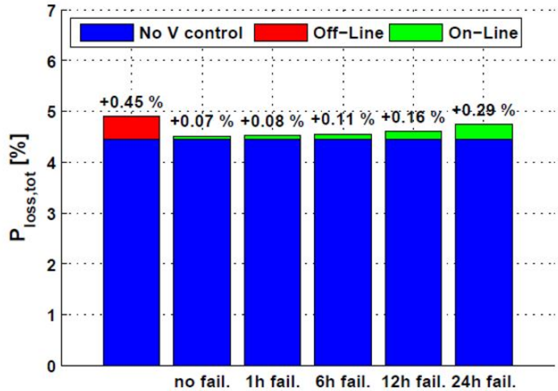

Fig. B.4: Average power losses over the simulation period for various durations of communication failure for updating the voltage set-points [15]

regulation within the distribution grid due to hunting effects between the individual controllers. In case a hacker is able to manipulate the droop values accordingly, by attacking the aggregator control unit and sending updated reference signals to all ReGen plants, severe grid situations can occur. This is illustrated by Figure B.5, showing the voltage and reactive power profile for a case when all droop values are set to 0.5%, leading to a very flat droop characteristic.

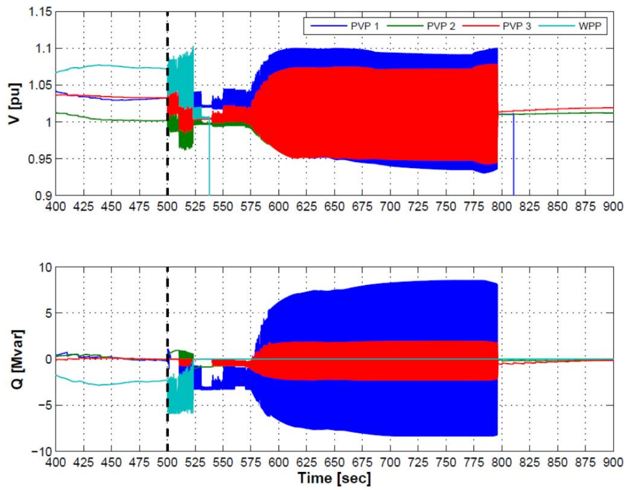

Fig. B.5: V and Q of all ReGen plants when subject to a cyberattack (manipulating droop value at t = 500 s)

At t = 500 seconds, the cyberattack (in terms of manipulation of the droop values) is initiated, leading to subsequent voltage oscillations. At t = 524 seconds, the WPP experiences a voltage exceeding the limit of 1.1 pu and needs to shut down. Voltage oscillations between all PVPs sustain, until PVP 1 shuts down at t = 795 seconds due to over-voltage.

Figure B.6 shows a case where the hacker was capable of manipulating the voltage set-points being sent from aggregator to the ReGen plants. At t = 500 seconds, a reference signal of $V_{set} = 1.08pu$ is sent to all ReGen plants, which instantaneously leads to a rising voltage profile in the distribution feeder. At t = 567 seconds, the WPP shuts down due to overvoltage. The remaining PVPs will eventually provide reactive power (+Q) to boost the voltage according to the droop characteristic with the relatively high voltage set-point.

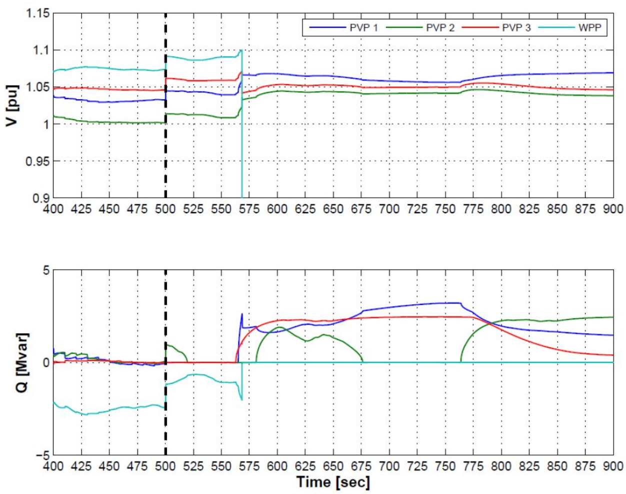

Fig. B.6: V and Q of all ReGen plants when subject to a cyberattack (manipulating voltage set-point at t = 500 seconds)

B.4.3 Test Summary

The impact of cyberattacks on on-line voltage control coordination can be summarized by means of SGIS five scale likelihood levels in [5], as presented in Table B.1.

B.5 Cyber-Security Solutions

Cyber-attacks can be mitigated in many ways, depending on the attack vector among other things. Two approaches to handle the cases described above are introduced in the following.

Table B.1: Impact of cyberattacks on on-line voltage control coordination –SGIS likelihood levels

Security Level	Effects of Cyber-Attacks
Critical	False Message Signals
Medium	Latency up to Several Hours
Low	Latency from Seconds to Minutes

B.5.1 DDoS Scrubbing Centers

A small volumetric DDoS attack towards a server in a datacenter can possibly be handled by provisioning network capacity accordingly and well in advance. This is expensive as the excess capacity is wasted when there is no attack, which presumably is most of the time. For large volumetric attacks this approach is infeasible, and instead it is common to rely on so called DDoS scrubbing centers [11]. As shown in Figure B.7, all traffic to protected systems is routed through a DDoS scrubbing center, rules and proprietary methods are applied to filter out DDoS traffic. Legitimate traffic is ideally simply passed on to the protected services. Such centers generally claim to introduce no significant delay, as it merely modifies the BGP routing that is already done on the internet, and performs filtering at line speed. As these centers are specialized in handling DDoS attacks, they can provide network capacity to handle large DDoS attacks. In cases where DDoS traffic exhausts even scrubbing center capacity, or if such centers are not used, traffic from all or some parts of the internet can be dropped by modifying the BGP routing. Scrubbing can be always-on, such that no significant amount of traffic reaches the target. It can even be on demand, meaning that the DDoS traffic will hit the target for a few minutes, until the service is enabled. Thereby, imposing minor impact on the power losses.

B.5.2 IPsec Protocol

The TCP and IP protocols that make up the Internet provides no confidentiality nor authenticity guarantees. When a determined attacker compromises the trivial security mechanism of the lower layers (e.g. physical security, network segmentation) the attacker can perform attacks like the TCP reset attack described in Cases 3 and 6 in Section B.3. A precondition for this attack is that confidentiality is breached, such that the attacker can learn the states of the TCP connections, and that authenticity is breached, such that the attacker can pretend to be the other party of the connection. The commonly deployed SSL/TLS protocol provides the required guarantees, but relies on the TCP protocol, hence it cannot mitigate the TCP reset attacks. IPsec is an-

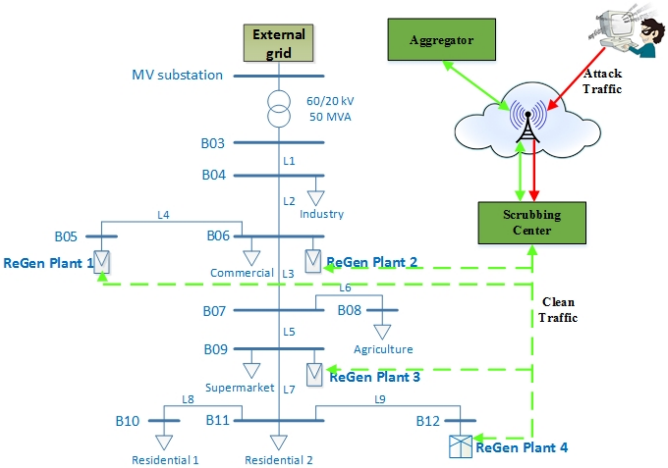

Fig. B.7: Use of Scrubbing Center for clean traffic

other protocol providing the required security guarantees. IPsec replaces the IP protocol and encrypts the wrapped TCP packet, among other things, providing authenticity and confidentiality. This stops attackers both from learning the TCP connection state and from impersonating a connection party, thereby thwarting the TCP Reset attack. Using IPsec have a price though, which comes in the form of protocol overhead. Since IPsec always require ESP header for the confidentiality issues, it has the highest communication overhead among other security protocols [6]. The communication overhead causes end-to-end delay to be affected the most by IPsec [6]. However, since the additional delay lies within a range of milli-seconds to seconds [6], it will not have much impact on the performance of the system, as ascertained in Section B.4.

B.6 Conclusion And Future Work

Cyberattacks are an important issue for smart grid communication. This paper elaborates the impact of cyberattacks on on-line voltage control coordination from ReGen plants in a smart grid scenario. Various aspects related to the possible cyberattacks are evaluated with respect to the related latencies and validity of the signals being exchanged between aggregator and ReGen plants, resulting in deviating voltage control performance in the distribution grid. Based on the criticality of power system infrastructure, cyber-security solutions must be in place to provide a secure cyber environment. Although there exist many traditional cyber-security solutions that can be used to secure communication in smart grids, a lot more research has to be done.

Here we have identified only two of such security solutions in this paper to stop/mitigate the effects of these cyberattacks. The motivation for this paper was specifically to analyze the impact of various cyberattacks on the performance of online voltage control coordination. However, as a future work the authors are currently working on implementing various cyber-security solutions in a test-bed (including IPSec and DDoS scrubbing center) to analyze how effective these solutions are to provide cyber-secure environment to the future smart grids.

Acknowledgment

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Paper C

ICT Based HIL Validation of Voltage Control Coordination in Smart Grids Scenarios

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Abstract

This paper aims to validate the capability of renewable generation (ReGen) plants to provide online voltage control coordination ancillary service to the system operators in smart grids. Simulation studies about online coordination concepts from ReGen plants have already been identified in previous publications. However, here, the results are validated through a real-time Hardware-In-The-Loop framework using an exemplary benchmark grid area in Denmark as a base case that includes flexible renewable power plants providing voltage control functionality. The provision of voltage control support from ReGen plants is verified on a large-scale power system against the baseline scenario, considering the hierarchical industrial controller platforms used nowadays in power plants. Moreover, the verification of online voltage control support is carried out by taking into account a communication network as well as the associated data traffic patterns obtained from a real network. Based on the sets of recordings, guidelines and recommendations for practical implementation of the developed control algorithms for targeted ancillary service are made. This provides a deep insight for stakeholders i.e. wind turbines and photo-voltaic system manufacturers, system operators regarding the existing boundaries for current technologies and requirements for accommodating the new ancillary services in industrial application.

C.1 Introduction

Currently, in Denmark a large part of the power from Wind Power Plants (WPPs) (i.e., 3799 MW) is coming from onshore wind turbines [1, 2]. These wind turbines are distributed either individually or in small-scale clusters. Conversely, the power from Photovoltaic (PV) production primarily consists of small dispersed residential units up to 6 kW [3]. Additionally, the Danish Government targets achieving 50% of the total power production from renewable energy by the end of 2020 and 100% by 2050 [4]. In the coming years, this anticipated trend will lead to the integration of huge concentration of not only offshore and onshore WPPs but also a large scale concentration of PV Plants (PVP) in transmission as well as distribution system, respectively [5]. This foreseen huge penetration of ReGen plants into the Danish electricity supply may possibly create several challenges, as discussed in [1, 2, 6]. A simple solution proposed in [1, 6] is the provision of online reactive power support from the existing ReGen plants in the distribution grid. The provision of online voltage/reactive power support will allow down regulating the entire voltage profile in the distribution system, and also keep the voltage within the limits at the given nodes. Moreover, this capability is also required by today's grid codes and has already been implemented in modern ReGen plants. Nevertheless, owing to the lack of technical infrastructure for communication and control, this capability is not yet utilized by the Distribution System Operators (DSOs). Considering the increasing number of dispersed units, an effective coordination between these units along with local control of voltage on a distribution grids is required to provide reactive power support. The DSOs in Denmark have already started to install a Supervisory Control and Data Acquisition (SCADA) system for this purpose that will be employed in the near future [6]. On the other hand, in the absence of a regulatory framework, controlling the ReGen plants for reactive power support may not be reasonable in short term.

It is also pertinent to note that Networked Control Systems (NCSs) are known to be sensitive to the changing communication network properties, such as end-to-end delay and information loss rate, which can cause serious control performance degradations. Communication disruptions in control loops may in turn have serious consequences on the physical systems that are being controlled over communication networks. In SG, these disruptions can manifest themselves as over-voltages, physical damages in the power grid and in worst-case can lead to blackouts. Similarly, relying on the underlying communication networks to address voltage stability challenges (e.g., related to volatile voltage excursions in distribution systems) in power systems with large penetration of ReGen plants will put high responsibility on these networks. The authors have demonstrated the impact of using public network communication (i.e., cellular networks) for voltage control coordination from ReGen plants in [7, 8], and also highlighted the challenges and risks associated to the use of Information and Communication Technologies (ICT) in the said scenario.

The integration of ICT into the electrical energy infrastructure is shifting from a phase of demonstration to large-scale deployment [9]. This will not only have a strong impact on system architectures but it will also raise concerns about the issues related to cyber-security. The integration of ReGen plants (such as PVP, WPP, etc.) as well as the communication technologies in power grid has made it a cyber-physical energy system, also termed as Smart Grid (SG). A general framework for SG is therefore required for the validation that takes into account the mutual interactions and interdependencies between ICT and ReGen. However, today, lack of design and validation tools that are capable of analyzing power systems in combination with the ICT in a holistic manner is one of the main barriers.

Incorporating power system simulation tools with that of ICT requires collaboration among experts of both areas. This is because of a significant difference in both communication as well as electrical related equipment (including but not limited to messaging protocols, information models, reliability requirements, temporal consistency, hierarchy, etc.) [9]. Here, a co-simulation platform for the integration analysis of both domains helps in understanding the impact of different ICT based solutions used for the operation of power systems. After solving the subsystems independently by their corresponding domain specific simulators [10], co-simulation allows a joint and simultaneous investigation of models based on different tools, where intermediate results are exchanged during the execution of the simulations [9, 10]. Therefore, co-simulation makes it possible to have a comprehensive view of the network behavior in connection with the physical energy system states. Further, before the implementation and roll out of the simulation studies, these should pass through a Real-Time (RT) simulation environment to test the controller design. This RT simulation shows how the designed controller responds, in real time, to realistic virtual stimuli. It can also be used to determine if the designed physical system model is valid or not.

It can be ascertained from the above discussion that there are several stages in the design and implementation of a SGs related concepts, which should be carried out in a sequential and hierarchical fashion. Thus, as a first contribution, this paper introduces a Model-Based Design (MBD) approach in SGs that proves to be an important methodology in the design, implementation and roll out of SG technologies, solutions and corresponding products. In addition to the several benefits, this approach will offer collaboration among different laboratories at international level, which, in turn, has a positive impact on interoperability and confidence in the applicability of the research under different grid conditions. Additionally, as a part of MBD, this paper demonstrates the provision of online voltage control coordination support from ReGen plants via a Real-Time Hardware-In-the-Loop (RT-HIL) framework. This RT-HIL framework is available in Smart Energy Systems Laboratory (SES Lab) [11] at the Department of Energy Technology, Aalborg University, Denmark. It uses hierarchical industrial controller platforms, e.g., Bachmann's M1 controller [12], that are used nowadays in power plants. This testbed has been used for several projects in the past, such as [13–15].

The concept and design of online voltage support from ReGen plants has already been published [1, 6, 16], while the authors in [7, 8] have illustrated the impact and associated risks (such as cyberattacks) of using existing public network communication infrastructure on the online voltage control coordination from ReGen plants in distributed grids, respectively. Since the work presented in [1, 6–8, 16] is mainly based on offline or non-Real-Time (non-RT) co-simulation framework, the authors in this paper prove through real-time set of recordings that the control concepts developed in [1, 6, 16] are valid. The validation is done by first verifying and validating the proposed ICT model for non-RT studies in [7, 8] through different test cases against the complete network model and related data traffic implemented in the SES Lab. Based on the results, the validation of coordinated voltage control for ReGen plants in Medium Voltage (MV) grids is achieved.

Hence, the scope of this paper is two-fold: **(1)** its introduces an MBD approach in SGs as an important methodology in design, implementation and roll out of SG technologies; and **(2)** as a part of MBD approach, it validates the already presented concepts and results related to the provision of online voltage control coordination support from ReGen plants via RT-HIL framework. The remainder of this paper is organized as follows: Section C.2 introduces MBD and explains the different stages involved in this approach. A brief description related to the concept of distributed online voltage control concept that was presented in previous publications along with its RT-HIL setup implementation description is presented in Section C.3. The details and challenges related to ICT simulation model in providing the online voltage control support from ReGen plants are outlined in Section C.4. Section C.5 provides the assessment and validation of both ICT simulation model as well as the RT voltage control coordination concept. Finally, the study is concluded with future research directions in Section C.6.

C.2 Model Based Design in Smart Grids

Today's control capabilities for power systems and SGs are more and more demanding, especially with high share of power generation from renewable sources. Design and tuning of control algorithms is typically based on dedicated simulation tools, e.g., MATLAB/Simulink, while control verification may require other power system tools. Translation of control schemes between tools may be time consuming and the typical iterations in control development may increase the time even more. Once the control schemes are verified in a power system tool under various operating conditions and test cases, an implementation phase on the actual target hardware is required. Another series of tests are then required to validate the implementation. Finally, the controller is tested in a real environment. Some of the measurements are later used to validate the designed control performance but also the models used in the design process. It is worth mentioning that site testing may not involve specific tests that require measurements of real events in the power grid. Thus, typically, open loop testing is performed. Some of these events, e.g., large frequency excursion, may not occur during the limited testing period of controllers.

To overcome some of the drawbacks encountered during the design and testing of control schemes for power systems and SGs, an MBD approach is employed. The MBD approach was initially used by automotive industry and then for motor drives [17]. A brief history of MBD can be found in [18]. The different stages used in designing and testing of control schemes for power systems while employing the MBD approach are shown in Figure C.1. An overview of these stages from development to testing is presented in the following subsections.

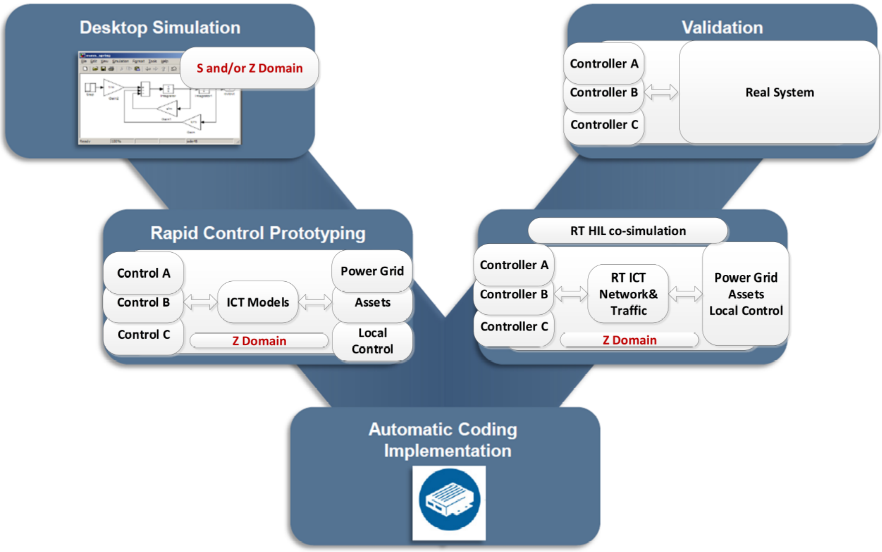

Fig. C.1: Model-based design approach for power system and SG applications.

C.2.1 Desktop Simulations

Initially, the control development and tuning process uses simplified/reduced order models of power system and assets. Either continuous or discrete time models can be used according to the tuning methodology [17]. However, a continuous time domain tuning is preferred at this stage [17] because the dynamics in the power system applications involve a wide range of time constants as well as various sampling times for the related subsystems. Further, considerations about translation of models in discrete models are made in respect to the actual expected sampling time of various control platform used.

C.2.2 Rapid Control Prototyping

In this stage, the entire model is implemented in discrete domain with the proper sampling time for various subsystems. This model is implemented in a RT discrete simulator, e.g., Opal-RT. The control algorithms are tested intensively under various operating conditions to identify the robustness of the design. Based on the executed tests and their results, iterations of the control design and tuning may be necessary. It is worth mentioning that information exchange between different subsystems, i.e., plant controller, aggregator, assets, etc., is also captured at this stage with a dedicated model that is able to simulate the communication networks and their traffic (see Section C.4). By using dedicated communication models for information exchange, it can be identified if specific ICT can meet the requirements imposed by control response. Moreover, this helps to specify minimum requirements (or boundaries) for ICT to provide a specific control function. This will allow the selection of the ICT for the deployment. Finally, the control is ready for implementation on the target hardware when the control design verification is finalized.

C.2.3 Automatic Coding Implementation

Typically, target hardware requires coding of control algorithms in different software, specific to manufacturers of the platforms e.g., structured text, C/C++, etc. This process can be shortened if the simulation tools used for control design are capable of generating the code automatically, such as MATLAB/Simulink. Since, SES Lab already uses the MATLAB/Simulink platform to design and simulate controllers as well as to translate to the required code, this step can be skipped when using the facilities in this lab.

C.2.4 RT-HIL Co-Simulation

Verifying control algorithms on large-scale power systems requires testing of the controller platform connected to a RT model of the power system including assets i.e., WPP, PVP, energy storage devices, etc. Moreover, for a realistic testing, RT model of the communication networks is used. Thus, the controller platform including the developed algorithms in the first phase is tested in realistic conditions close to daily operation. Moreover, power system events that cannot be measured in real life can also be replicated in a controlled environment, for instance, during extreme weather conditions for both WPP and PVP. Similarly, the normal data traffic associated to specific network technologies as well as with failure conditions (e.g., due to cyber-attacks) is captured without actually involving the real technologies. The advantage of this approach can be summarized as:

- Extensive testing and verification of control algorithms under operating conditions which cannot be encountered during the field-test trials.
- Accounting for impact of communication technologies, protocols and traffic on the developed control algorithms in a unified and consistent without being constraint by the physical systems.

The developed control algorithms including physical implementation on target hardware is then ready for site testing. This stage corresponds to a Technology Readiness Level (TRL) of 6. According to HORIZON 2020—Work Programme 2014–2015 [19], TRL-6 stands for the demonstration of technology in a relevant environment, i.e., industrially relevant environment in the case of key enabling technologies [19].

C.2.5 Validation

Once the designed controller is passed through all aforementioned stages, it has to be validated using actual plant hardware in real-life situations. The main goal for this process is to ensure that no physical equipment will be damaged during the tests. For this, the actual controller platform should be tested on-site under operating conditions allowed by the physical power grid and assets. Typically, the targeted tests have to be reported and documented to power system operator (DSO or Transmission System Operator) as well as to the plant operator or owner before execution. However, this process becomes complicated in terms of coordination, etc. when different owners/operators are involved. Moreover, the testing campaign is typically limited in time and power system events in scope for the developed algorithms and, therefore, large voltage and frequency excursions may not occur in the system during the testing period. Thus, an open loop approach is used. This means that the controller is fed with pseudo-measurements and the output of the plants is recorded. However, the actual impact on the power grid cannot be evaluated as well as possible control interactions between assets. These recordings may be used to validate some of the developed models including modeling assumptions used in the previous stages. This is where a RT-HIL again plays its role and allows tests and validation without even involving the physical power grid and assets. By allowing to use the designed model to represent the real-life scenario, RT-HIL platform offers benefits in terms of cost and practicality [20].

The existing facilities in SES Lab [11] allow all of the above design and verification procedure being a powerful environment for achieving high TRLs. Therefore, in the following section, we first present a brief overview of the distributed online voltage coordination concept from ReGen plants, established in [16], and subsequently the implementation of this concept in the RT-HIL setup in SES Lab is described.

C.3 Distributed Online Voltage Coordination Concept and RT-HIL Framework

According to the Grid Code requirements, the voltage profile in a power system should remain within the desired tolerance band. For instance, in MV distribution grids, the voltage should remain within $\pm 10\%$ of its nominal value [16]. This challenge has to be fulfilled by each generation unit connected to the power system. The violation of this limit at certain points within the grid may possibly lead to severe stability problems and damage to the entire power system [6]. Although each ReGen plant can contribute to voltage regulation, as ascertained in [7, 16], there can be additional control objectives required by the DSO, for example to reduce the grid power losses caused by reactive power provision. This objective can be accomplished by optimizing the control settings in the distributed online coordination scheme, as defined in [16], which constitutes an NCS of the SG developed on top of a communication network. The basic NCS architecture for distributed online voltage coordination is given in Figure C.2.

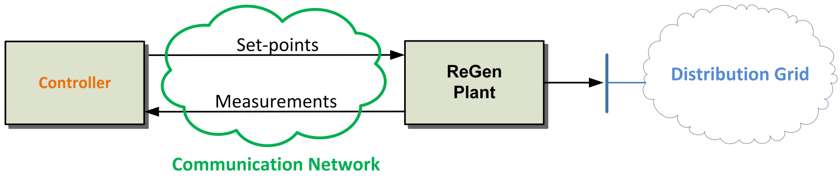

Fig. C.2: Basic NCS architecture for distributed online voltage coordination.

This control architecture requires a grid layout and parameters provided by the DSOs, measurements from secondary side of primary substations as well as measurements from each of the controlled ReGen plants. It provides voltage setpoints and droop values for each ReGen plant considered in the asset's portfolio. Since the power output of ReGen plants continuously varies and thus the voltages in the distribution grid, it is foreseen that an aggregator of grid support services may take over the task in future. This aggregator will be responsible for continuously updating the controller settings of the ReGen plants in real-time according to the actual operating point. The detailed NCS architecture for distributed online voltage coordination is given in Figure C.3. The aggregator (indicated as Distributed Online Coordination block in Figure C.3) receives measurement signals i.e. voltage, active power, reactive power (V_{meas},P_{meas}, Q_{meas}) and the available reactive power (Q_{ava}) from all ReGen plants (1...N) and in return dispatches the droop settings (V_{stp}, $droop$) for the voltage controllers.

Further, a Benchmark Distribution Grid (BDG) was developed in [16] to identify voltage stability challenges in distribution systems with large penetration of ReGen and to assess the voltage control functionalities shown in Figure C.3. The BDG is based on a real MV grid operated by Himmerland Elforsyning (HEF) near Aalborg City in North Jutland, Denmark, and is considered as starting point for the definition of the BDG. To account for realistic scenarios regarding the current and future penetration of renewable power plants in Danish distribution grids, the BDG has been supplemented by the following ReGen plants providing voltage control functionality, i.e., one WPP with type-4 (full-scale converter connected) wind turbines and three PVPs:

1. WPP (18 MW) representing 6 WTs of 3 MW each
2. PVP 1 (10 MW) representing remotely located ground-mounted system

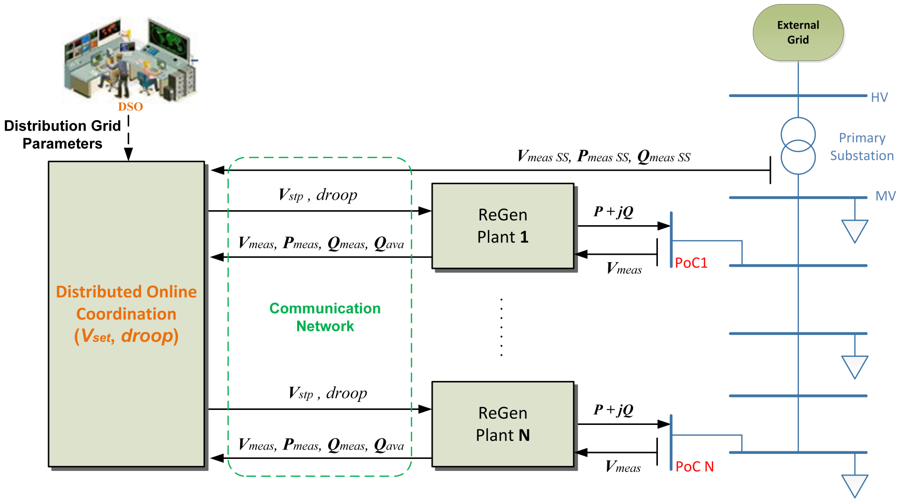

Fig. C.3: Control architecture for distributed online voltage coordination.

3. PVP 2 and PVP 3 (2.5 MW each) representing typical rooftop systems mounted on top of large industrial plants and shopping centers

The BDG represents a typical radial feeder topology with primary substation (60/20 kV) as shown in Figure C.4, where the ReGen plants are shown as WPP, PVP 1, PVP 2 and PVP 3 (the BDG model is presented in detail in [16]). Based on the control architecture shown in Figure C.3, this BDG is used to analyze voltage control in time domain for a volatile power profile of the ReGen plants, used as a benchmark test scenario that covers the crucial operating points with high solar irradiation and high wind speed (for details, see [16]).

The authors have demonstrated in [16] that, using the NCS architecture shown in Figure C.3, the overall performance of online coordination for voltage profile management, control stability and the present voltage fluctuations remained satisfactory. The power losses within the distribution grid have also been shown to reduce to a measurable extent. Concerning the intervals at which the voltage set-points are to be updated, the authors demonstrate it via several test scenarios in [16] that the aggregator should dispatch set-point signals to ReGen plants in time intervals of 10 s to few minutes. However, it has also been recommended that power losses need to be evaluated for longer time periods (such as months or years) to provide meaningful recommendations for the controller specifications, taking into account the economic benefits for a DSO.

The following subsection elaborates on the implementation of the described distributed voltage control coordination concept along with the BDG

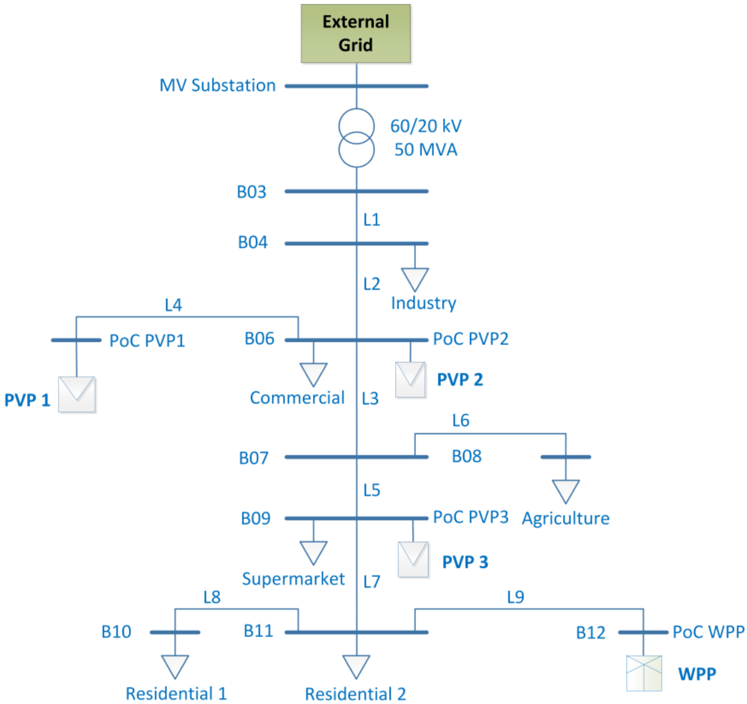

Fig. C.4: Structure of the MV benchmark grid.

in the RT-HIL setup.

C.3.1 RT-HIL Setup

SES Lab was used to implement the control architecture for distributed online voltage coordination in the RT-HIL framework. Figure C.5 shows the front view of this lab with various subsystems and workstations involved in the RT-HIL setup.

Figure C.6 illustrates the setup used for the implementation of control architecture for distributed online voltage coordination in the RT-HIL framework seen in the lab. Before presenting the overview of each subsystem shown in Figure C.6, it should be noted that in the near future an ancillary market is also expected for the provision of grid support services [21]. It is foreseen that in close collaboration with local DSOs, the aggregators of Re-Gen plants will take the charge for hosting voltage control capabilities besides energy trading [6]. Therefore, at this stage, it is assumed that the aggregator control unit is in charge of providing reactive power support along with controlling voltage locally on the distribution grid. In the following, a brief overview of each subsystem shown in Figure C.6 is presented (for detailed

Fig. C.5: The various subsystems and workstations involved in the RT-HIL setup available in SES Lab at the Department of Energy Technology, Aalborg University, Denmark [11].

description, see [17]):

1. Aggregator Hardware Platform is based on the M1 controller hardware provided by Bachmann Electronics Gmbh [12]. One reason for choosing this platform is that it supports the MBD approach using MATLAB/Simulink. Moreover, it is widely used in the renewable energy industry and hence considered as a benchmark system. In the context of research applications of SG scenarios, this controller platform offers the possibility of utilizing open communication protocols (e.g., User Datagram Protocol(UDP)/Internet Protocol(IP)) for the data exchange. In this way, the obtained results for RT-HIL validation are not affected by any manufacturer specific protocols, which may introduce additional delays, etc. In the current setup, the M1 controller receives measurements from primary substation and ReGen plants (implemented in Opal-RT System), and provide voltage set-points and the droop values, respectively, through the RT ICT Emulator. It is important to note that the distributed online voltage coordination scheme presented in [16] is used as such. The only modifications are related to Transmission Control Protocol/Internet Protocol i.e. TCP/IP interfaces between different hardware platforms.

2. Host PC—Aggregator Hardware is a dedicated Professional Computer (PC) used for developing the initial controller schemes in MATLAB/Simulink. It is also hosting the dedicated software to communicate with the controller for setting up the configuration of the controller.

3. Opal-RT System [22] hosts the BDG. It sends measurements to and receives set-points from the Aggregator Hardware through RT ICT Emulator. The grid layout and ReGen plants RT models are developed using ePHASORsim tool from RT-Lab [23, 24]. The wind power plant

and solar PV plant models defined in [19] are directly implemented in the Opal-RT System.

4. Host PC—Opal RT is a PC dedicated for the development, control and monitoring of the RT model. Automatic code generation of the RT Model is included in the RT-Lab suite [24] provided with the Opal-RT system. The Monitoring and Control Module is sending the following signals to the Opal-RT System:

    (a) Meteorological data: wind speeds, solar irradiation
    (b) External grid voltage setpoint
    (c) Load profiles in terms of active and reactive values

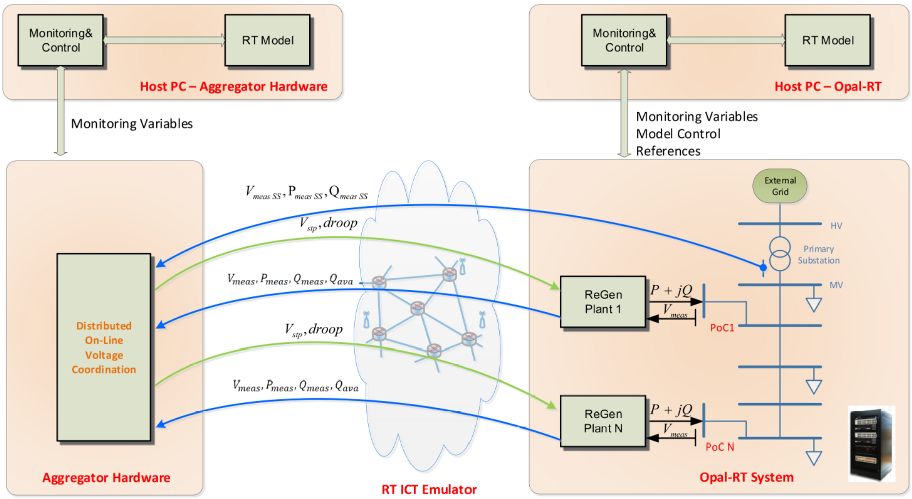

Fig. C.6: RT-HIL setup used for validation of distributed online voltage coordination.

This module also receives selected signal from the Opal-RT System for monitoring the model performance during simulations.

5. RT ICT Emulator. The RT network emulator is based on KauNet [25] that provides pattern based network emulation by enabling ingoing as well as outgoing data packets to pass a queue configured with a buffer length and service time according to a given stochastic model of a network. KauNet provides control on bit errors, packet losses, bandwidth, and delay changes. Using KauNet, reproducible behavior of network along with an exact control on network traffic over Internet can be provided [26]. The traffic using KauNet is routed through a set of buffers, where each buffer emulates specific network characteristics in terms of delay, packet losses, etc. [26]. The network capacity can also be

emulated by shaping the buffer sizes, such that packet losses can be efficiently emulated. The idea behind this setup is to have flexibility to assess any types of networks as well as the power control systems networks that generally are more deterministic in nature. Further, it is meant to illustrate the strength of being able to assess control over third party stochastic-networks which is highly relevant for operators to assess their possibility to support connectivity services to DSOs.

All the data exchange between aggregator hardware and Opal-RT system is executed through the RT ICT Emulator. This means that only these signals are prone to delays, packet drop and cyber security threats. The data exchange between host PCs and corresponding hardware is not affected.

C.3.2 Considerations on Real Time Implementation

The various subsystems presented in Figure C.6 are running with different sampling times to capture the realistic behavior of such a system used in real applications. The following considerations are made regarding specific sampling time.

(i) Host PC-Opal RT: The Monitoring and Control Module uses a 200 ms sampling time for sending the meteorological data as well as for monitoring of the internal variables from Opal-RT System. The reason for this fast sampling is the available time resolution of meteorological data (i.e., wind speed and solar irradiation).

(ii) Opal-RT System: The power grid and the ReGen plants are running with 10 ms sampling time as a standard value for Root Mean Square (RMS) simulations (half cycle of 50 Hz system). The feedback signals from ReGen plants and primary substation to Aggregator Hardware are updated every second. This sampling rate is chosen to exchange steady-state signals, as the typical time response value for the active power control loop of Wind Turbine Generators (WTGs) is below 1 s [16].

(iii) Aggregator Hardware: The sampling time for distributed online voltage control coordination algorithm depends on the sending of set-point values as per the update rate [16].

C.3.3 Summary of Involved Hardware/Software Platforms

Given a variety of hardware/software environments used in this work, Table C.1 summarizes the involved suites, indicating their role to facilitate the understanding of interconnected functions and to provide the whole perspective about the presented approach.

Table C.1: Summary of involved suites and their role description.

Hardware/Software Platform	**Description**
M1 Controller	Used to implement RT aggregator control unit via MATLAB/Simulink.
Opal-RT	Used to model BDG, ReGen plants and external grid via RT-Lab/ePHASOR.
KauNet	Software used to emulate communication network for point-to-point communication via real network based data traffic.
MATLAB/Simulink	Used for design and verification of controllers.

C.4 Information and Communication Technologies (ICT) Model

An essential feature of the distributed online voltage coordination is the use of ICT for gathering and acting on information collected from various ReGen plants in an automated fashion. To enable bi-direction information flow for this purpose, various communication technologies can be used. These technologies include wired (such as copper cable and fiber optics) and wireless (such as WiMAX and cellular networks) public/private networks. Utilizing existing Internet access networks is a viable and cost-effective solution offering a good coverage in most European countries [27]. However, networks providing Internet access have time-varying network properties. This particularly creates a problem for NCS, where the main issue that causes degradation of control performance are network induced time-varying delays and packet losses [27]. Furthermore, as the communication systems (specifically wireless Internet access communication networks) are becoming more and more complex with decreasing time-to-market, accurate simulations models of upcoming standards are essential. The accuracy of these models becomes even more significant when used in combination with critical systems such electrical power systems. It requires to have more detailed view of the communication system and considering extra details when designing the controllers. For instance, when designing a communication system model, the several features to be taken into account are the offered load, traffic patterns, information loss, end-to-end delay, etc. Thus, communication models that reflect real life scenarios (in terms of end-to-end quality of service) should be considered even during the designing phase to depict true impact on the system's performance.

The simulations related to power system controllers (such as, the voltage controller in this paper) are often done using the Simulink toolbox for MATLAB, where MATLAB/Simulink is based on vectors of bits/symbols/samples. The majority of such MATLAB implementations usually deal with equivalent symbol timing and bypass network aspects beside interference within physical frames. According to [20], network protocols (TCP, IP), network topology and queuing are rarely considered due to the complexity issues, because each time a new random parameter (such as queue length, etc.) is introduced, the computational complexity increases (at least) linearly ($O(n)$). Similarly, the computational complexity of the simulations increases as a polynomial function ($O(n_c)$) or even exponentially ($O(c_n), c > 1$) [20] with respect to the number of assets. This requires a higher level of abstraction as in the network simulators (such as ns-3, OPNET, OMNET++, etc.). Since there are no built-in libraries that allow networking considerations, MATLAB/Simulink (or similar tools) is not suitable for complex network simulations. In such a situation, indirect methods [20] can be used, i.e., creating interface between a network simulators and simulators like MATLAB/Simulink. Although MATLAB can be used via an interface (e.g., from C code) with the network simulators, the interfacing is not particularly easy to handle nor is it quite fast [20]. Moreover, since such interfacing methods require very detailed modeling, for larger and complex deployments, the methodology does not scale with regard to complexity. The simulation run time becomes so large that even for moderately complex topologies there is no (or very little) advantage left from the detailed simulation model. Likewise, evaluating simulation results becomes much more difficult because of a large number of parameters influencing the performance. Therefore, implementing a network simulation tool that supports control simulations with ease of handling should be highly preferred, especially for testing complex and critical systems.

Further, the tools used to simulate communication networks usually do not reflect the real life scenario, i.e., those are based on very low and deterministic latency without considering the geographical distances between communicating entities. However, in real scenarios the long geographic distance between different networked devices as well as the amount of traffic on the link may cause unexpected delays in transmission and even signal drops that result in unexpected and faulty control behavior. Specifically, while considering public network infrastructures for implementation, constant delays or packet loss probabilities do not depict the actual scenario. Therefore, dedicated communication network simulation tools are required that not only reflect real networks but also, in combination with the power system tools, assist in analyzing the effects of realistic latencies, packet losses or failures in the communication. Such communication simulators should also facilitate investigations related to cyber-security, such as Denial-Of-Service (DOS) protection, confidentiality and integrity testing.

C.4.1 Non-RT Communication Network Model

To comply with the rapid control prototyping stage described in MBD (see Section C.2), a network emulator was developed in Simulink that provides pattern-based network emulation. This network emulator, being implemented directly in Simulink, removes many complications such as time synchronization and interfacing between two different simulation tools. The patterns that describe the desired changes in the traffic can be created from analytical expressions or traces collected through a real network and are matched with traffic packets to required behavior in time driven mode. Thus, providing a user with a reasonable estimate of what end-to-end performance can be expected from a communication network. In this work, the patterns (based on end-to-end delays and packet loss) are obtained using NetMap [28, 29] (for details, see Section C.4.2). In addition to the pattern based network emulation, other relevant features of this network emulator are as follows:

1. Selection of transport layer protocols
2. Control over the sampling time (update rate) of information
3. Ability to introduce packet loss probabilities
4. Selection of information access schemes (reactive or proactive [30]) with control over the related parameters

C.4.2 RT Communication Network Model

The online coordination between ReGen plants and the aggregator highly relies on the underlying ICT infrastructure. This imposes huge responsibility on ICT to make sure that the connection is reliable and meet other requirements for the said purpose. At this stage, implementing a dedicated fiber optics connection to all ReGen plants in the grid seems the best possible option. However, using fiber optic communication in this case will be a highly expensive option considering the huge penetration of ReGen plants in the distribution grids. There are a number of other options too, as detailed in [31–33], but the authors propose to use an existing ICT infrastructure that could offer low operating costs, faster deployment, high speeds and flexibility along with the provision of full expertise and manning to operate the network. For instance, cellular networks (with technologies such as Universal Mobile Telecommunications System (UMTS), Third-Generation Cell-Phone Technology (3G), Fourth-Generation Cell-Phone Technology (4G), Long Term Evolution (LTE), etc.) are already extensively deployed by the telecom operators throughout Europe with high coverage [34]. Therefore, in their previous work [7], the authors demonstrated (via offline simulations) on the use of the existing cellular network communication infrastructure and showed how it effects the provision of online voltage control and coordination functionalities from ReGen plants in distributed grids. Through non-RT simulation results, it is shown in [7] that, under normal network conditions, the cellular networks support the proposed online voltage control and coordination functionalities for ReGen plants in distribution grids.

To validate the results obtained in [7] via RT-HIL setup, it is essential to get a realistic and accurate model of the cellular networks that reflect the true network behavior especially within the area having BDG (hereafter referred to as Benchmark Grid Area (BGA)). As KauNet has been opted in the RT-HIL setup as a RT network emulator that provides patterns based network emulation, the pattern files were captured from BGA using NetMap [28, 29]. The NetMap patterns are useful as they provide realistic performance under realistic conditions from networks that are normally hard to obtain information from/about, and are relevant, e.g., for operators to assess their possibility to provide connectivity service to control systems. Figure C.7 shows the map of BGA where the pattern files were collected. The map also shows Google map based locations of all ReGen plants in BDG along with the location of communication masts surrounding the area. Thus, the NetMap pattern files reflect the current nature of the access network in the relevant area.

It is pertinent to mention here that NetMap is a performance measurement system for mobile-networks that is based on crowd sourcing. It employs end user smart devices to automatically measure and gather network performance metrics from mobile networks. The obtained metrics comprise of throughput, round trip times, packet loss rates, connectivity, and signal strength, supplemented by a wide range of context information about the device state [28]. NetMap also offers a Network Performance Map (NPM) based on actual measurements on existing networks using actual end user devices in real end user scenarios. The measurements obtained via NPM are beneficial in the sense that these provide a more realistic image of what the end system can expect if the measurements are performed with similar devices [28]. According to the obtained measurements [28], the existing public network infrastructure can sufficiently fulfill throughput requirements to support the amount of data in said scenario. Therefore, the analysis in this paper is based on the end-to-end delay along with the packet losses a signal might experience while travelling between ReGen plants and aggregator controller to understand the impact on the performance of voltage controller.

The pattern files obtained from BGA via NetMap include delay traces (in terms of Round Trip Times (RTT)) as well as packet losses measured using many end devices located at different distances from the aggregator control unit (which is assumed to be located in the primary substation, as shown in Figure C.7) The measurements in pattern files are based on around 3500 TCP-RTT measurement sequences at different distances/locations of the end devices from the aggregator control unit using three different Internet Service

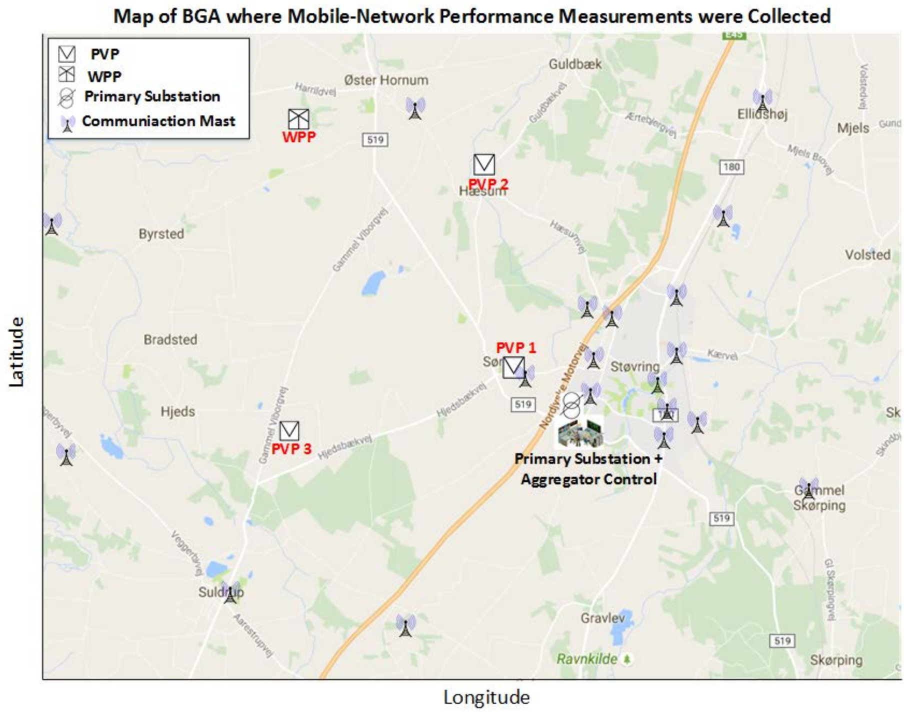

Fig. C.7: Map of BGA showing the locations of all ReGen plants in BDG and communication masts surrounding the area.

Providers (ISPs) available in Denmark. The three ISPs are referred as A, B and C in Figure C.8. Moreover, these measurements are based on 2G, 3G and 4G technologies. (Note: Since the data were collected via cell phones, they are not what a non-mobile electrical unit would accurately achieve in terms of network performance. However, it gives a reasonable estimate of what an asset can expect in terms of end-to-end performance from a communication network.)

Figure C.8(a) shows the combined histogram of RT-RTT measurements, while Figure C.8(b) shows the packet loss probabilities captured from BGA using several devices. It is important to note that the measurements shown in Figure C.8 have been obtained over a period of 1.5 years with varying number of end devices. In Figure C.8(a), it can be observed that, for majority of the cases, RTT lies around 30 ms approximately. This means that for a transfer of information update, a minimum of 15 ms delay (half of RTT—assuming the same route for request and reply to/from the server) can be expected for the maximum times in daily operations. However, as this network is heterogeneous (and shared by many users), the delay continuously varies depending on the network conditions and number of users using the network. The worst case for end-to-end delay is observed as high as 500 ms (RTT) (see Figure C.8(a). Further, Figure C.8(b) shows a varying number of packets sent along with the number of drop packets via different ISPs based on 2G, 3G and 4G technologies. Here, the number of packets sent through a particular technology depends on its available service within the BGA. 2G has the minimum number of sent packets because of its limited service available around BGA. However, according to Figure C.8(b), the packet losses observed while capturing these measurements were observed as high as 20% for 2G and as low as 0% in 4G technology.

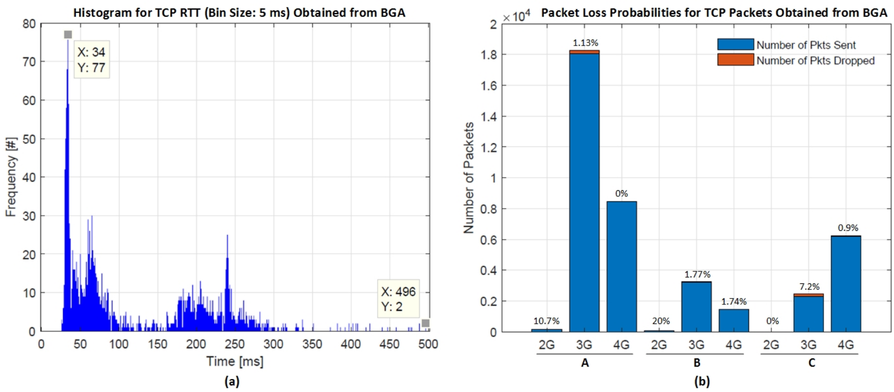

Fig. C.8: (**a**) Distribution of TCP RTT traces; and (**b**) packet loss probabilities measured around BGA using NetMap.

C.5 Validation of ICT and Voltage Control Models

The network simulator defined in Section C.4.1 was used as a non-RT communication network model for testing purposes. Generally, a non-RT communication network model is used in the design phase of any control algorithm as well as for verification purposes under a wide range of delays and packet drops. In this way, the simulation time for each test case is reduced and a complete view on the impact of ICT for a given control functionality is achieved. Selected test cases are then validated by using a RT communication network model in the RT-HIL framework. The main advantage of the RT-HIL approach is that the actual control platform is used with a RT model of the power grid and corresponding assets, i.e., ReGen plants, and also selected ICT including data traffic. These RT-HIL studies are mainly targeted to get confidence before actual site-test trials, as HIL simulations tend to be less expensive for design changes [35]. Moreover, specific power system phenomena can be replicated in this controlled environment that may not be detected in normal operation of the power grid. Therefore, in the following subsections, first the performance of non-RT communication network model will be validated via RT communication model and then selected cases from the distributed online voltage coordination will be validated via RT-HIL setup.

C.5.1 Validation of ICT Models

This section addresses the validation of the two communication network models defined in Section C.3. As a validation process, it is expected that both test setups show the same performance in terms of processing the signals. However, during the HIL based validation process, several faults can be expected, such as transient faults, intermittent faults or even permanent faults [36]. Here, the transient faults are induced by environmental conditions (e.g., noise, engine ignition, lightening, etc.) and are known to be less intense because such faults occur once and disappear. The intermittent faults are usually caused by non-environmental conditions (e.g., loose connection, etc.) and keep on repeating. The permanent faults are stable faults and continue to exist until the faulty components are fixed/replaced. All such faults may end up in adding bottlenecks to the communication link thereby saturating the network rapidly and resulting in: **(a)** increased delay in information transmission/reception; **(b)** increased information loss; or even **(c)** modification in the input signal. Therefore, it is important to keenly observe the results in the validation process of ICT models and make sure that the two communication network models show same performance.

Characterization of Test Setups:

To validate the non-RT ICT simulation model (see Section C.4.1) with its RT counterpart (KauNet) (see Section C.4.2), two test simulation setups (non-RT and RT) are implemented at this stage. With selected network parameters (based on delay and packet loss rates), identical signals were sent and received via both setups for comparison. The test setups are as follows:

Setup 1—Non-RT Model.

In this setup, the non-RT network simulator is used between a signal generator and the receiver (scope) to send signals under different selected network parameters, i.e., varying end-to-end delays and packet loss rates. The three components (i.e., signal generator, network emulator and a scope to capture output) reside in the same workstation in MATLAB/Simulink, as shown in Figure C.9(a).

Setup 2—RT Model.

In this setup, a signal generated at one working station was sent to the second working station through KauNet network emulator, as shown in Figure

C.9(b), with the same network parameters as in non-RT test setup. The original signal as well as the delayed signals were captured and recorded on working station 2 using MATLAB/Simulink. Connecting two workstations via KauNet requires defining IP addresses, port numbers, creating pipes between these ports, etc.

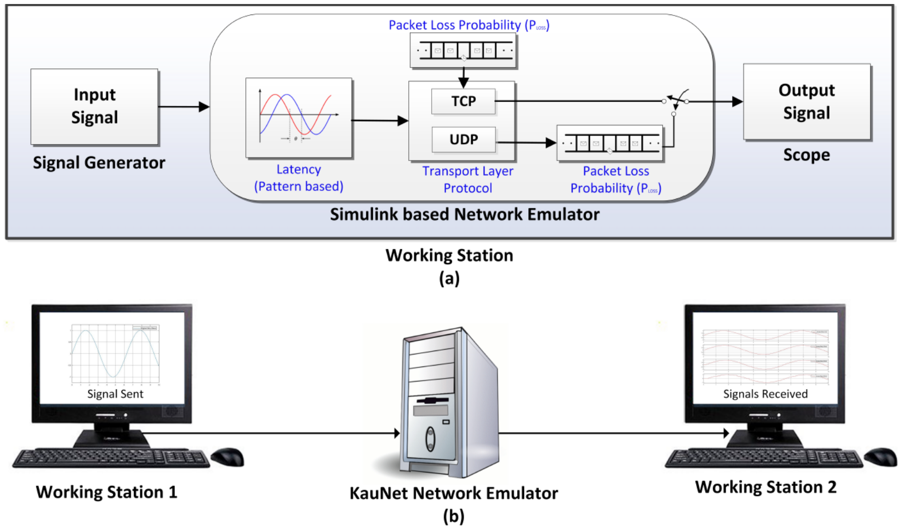

Fig. C.9: Test Setup: (**a**) non-RT network simulation; and (**b**) RT network emulation.

Test Cases for Validation of ICT Model

Two Quality-of-Service (QoS) parameters were considered in the test cases, i.e., delay and packet loss. Delay and packet loss are important QoS parameters as (in client/server communication) delay in data transmission can cause a server to make decision based on old data, or a client to change behavior based on old control messages, while packet loss in communication might mean that a server/client tries to make decision based on incomplete data.

Further, typically, to understand the impact of delay on information, a constant transport delay is used. However, in reality, data packets containing information might undergo variable delay based on the traffic on a link, number of users using the network, etc. For instance, in the case of public networks, where a huge number of people are using the same network, a constant delay cannot be guaranteed [28]. Thus, the delays in communication considered for test cases in this section are not constant delays. These delays are rather based on self-generated patterns with a specific average (mean) value. Therefore, it is expected from both test setups to shift each packet within the signal according to the generated delay patterns. Based on the average delays and packet drop rates, there are four test cases defined for both test setups (non-RT + RT), as shown in Table C.2.

Table C.2: Test cases for evaluation in non-RT and RT test setups.

Test Cases	Network Condition	Average Delay (ms)	Packet Loss (%)
1	Normal	10	25
2	Average	100	50
3	Below Average	250	75
4	Worst	500	90

Signal Characterization for Validation of ICT Model

As described in Section C.2, the models in desktop simulation can be continuous time or discrete time; thus, two signals were selected to validate the non-RT ICT model with its RT counterpart: (a) a pure sine wave representing a continuous time signal; and (b) a square wave representing a discrete time signal. Selecting a square wave signal is important, especially in the case where set-point values are sent (instead of a continuous-time signal, as in the case of ReGen plants coordinating with the system operator). The signals and parameters used are shown in Table C.3.

Table C.3: Signal Characterization.

Signal 1: Sine Wave	Signal 2: Square Wave
Amplitude: 10	Amplitude: 1
Frequency: $2 \times \pi \times 0.05$	Duty Cycle: 20%
Phase (rad): 0	Period: 0.1 s
Sampling time: 1 ms	Sampling Time: 1 ms

It is important to note that the purpose of selecting these signal parameters, i.e., much lower frequency for sine wave while very high frequency for square wave, is to visualize the impact of delay as well as packet loss in the signals, respectively. Complex signals could have been selected for this purpose but these simple yet useful signals were opted to serve the main purpose, i.e., the validation of ICT models. Figure C.10 shows the original (Figure C.10(a) sine wave and (Figure C.10(b) square wave signals used for non-RT as well as RT tests with the specified parameters. Similarly, it is worth mentioning that, although both signals were used to test the impact of added delays and packet loss probabilities in communication, not all results are added in this paper. Latency in a network is only shown for the sine wave, while packet losses are shown for the square wave (for detailed results, see [17]).

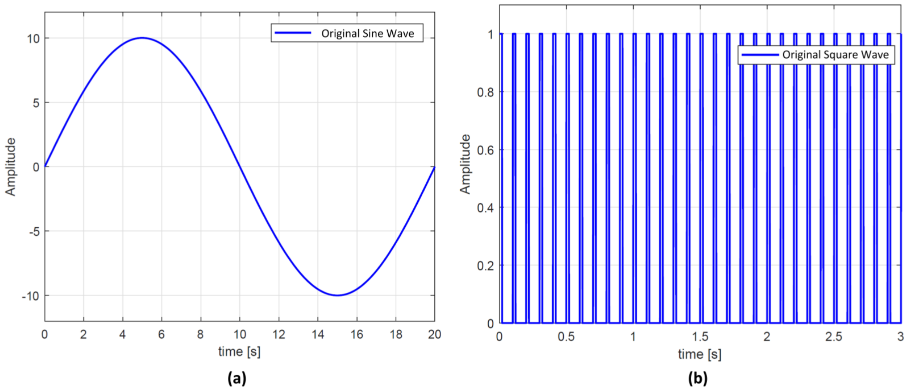

Fig. C.10: (**a**) Original sine wave; and (**b**) original square wave used in non-RT and RT tests to validate impact of delay on a signal.

Simulation Results and Comparison

Non-RT Setup—Test Results.
Figure C.11(a) shows the original sine signal compared to the ones received from network emulator under four delay based test cases. It can be observed how a signal can be affected due to different (average) delays in a network. It can be noticed that all received sine waves are steady state waveforms. This is because of a very high sampling rate selected (i.e., 1 ms). However, if the sampling rate is reduced, this will influence the shape of the incoming signal with each added average delay patterns. Figure C.11(b) shows the received square wave signals from network emulator under increasing packet loss rates in a network. It can be observed how a signal is affected with increased packet loss rates.

RT Setup—Test Results.
Figure C.12(a) shows the original signal compared to the ones received from working station 1 through KauNet network emulator under the four delay based test cases. As in non-RT results, it can be clearly observed how the sent signal is affected due to different (average) delays in a network. Similarly, Figure C.12(b) shows the received square wave signals from network emulator under four packet loss based test cases. It is worth mentioning here that the signals sent and received via the RT Setup were fully synchronized and started at the same time. However, since these signals were directly cap-

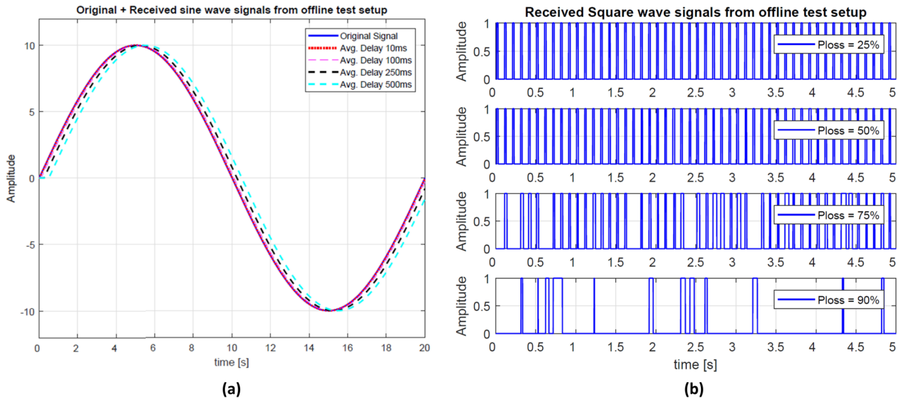

Fig. C.11: Test Results from off-line setup showing received: (**a**) sine wave signals obtained through a network with four different average delay patterns; and (**b**) square wave signals obtained through a network with four different packet loss rates with a Mean Squared Error (MSE) of around 5.0765×10^{-4}.

tured from a RT simulation setup, the signals in Figure C.12(a) seem shifted.

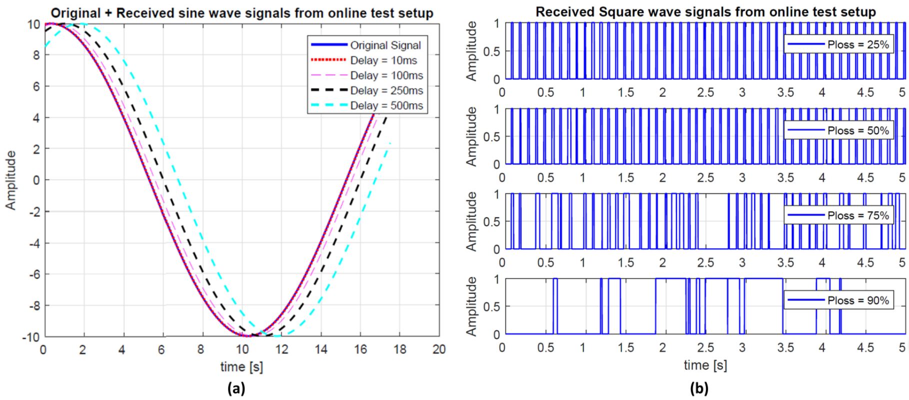

Fig. C.12: Test Results captured from RT setup showing received: (**a**) sine signals obtained through a network with four different average delay patterns; and (**b**) square wave signal obtained through a network with four different packet loss rates with MSE of around 5.0765×10^{-4}.

Figure C.13 captures the original sine wave with the ones received from non-RT as well as RT test setups (with average delay = 500 ms.) to show that the results obtained from both test setups are comparable.

Results Discussion and Summary

It can be observed from the test results that network delay in each case has the same effect on the signals. The faults discussed in Section C.5.1 have not

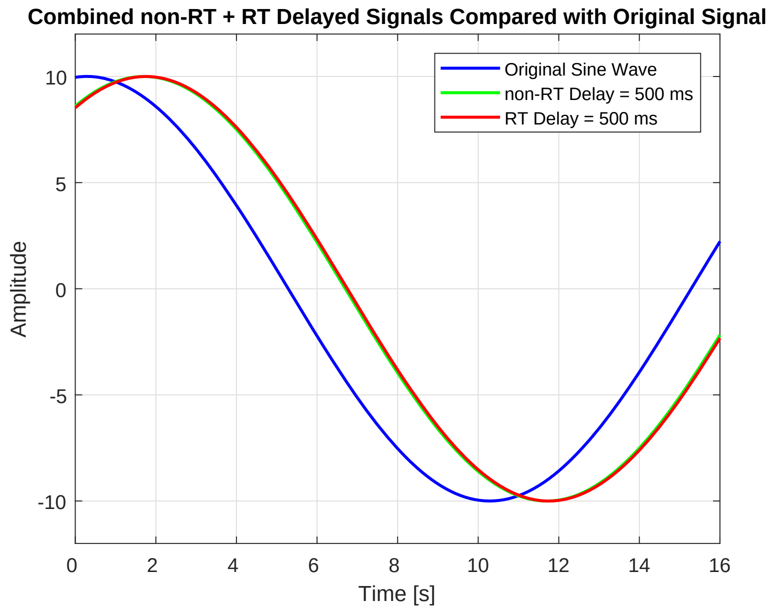

Fig. C.13: Original sine wave signal compared with delayed signals received from non-RT and RT test setups with MSE of 2.086×10^{-2}.

been observed, i.e. no additional delay or packet loss has been observed in either test setup. The impact of delay patterns with a specific average delay was not visible in any case due to the high sampling rate of 1 ms, while in the case of packet loss in square wave, it was expected that, with each packet loss rate, equivalent percent of bars will be seen to have dropped. However, it was revealed from the test results that each bar in a square wave comprised of several packets. Although the impact of packet loss was not apparent at 25% and 50% loss rates, it was observed (by magnifying) that, in each case, the shape of several bars in a square wave was deteriorated due to packet losses. Nevertheless, the overall response of non-RT ICT model matches the one provided by the RT network emulator under the same input and parameters. Thus, the non-RT communication network model proved to be a powerful yet simple representations of the communication networks and their traffic, especially for non-RT multi-run studies focusing on verification of control design. However, to gain complete confidence, selected test cases will go to a validation stage in the RT-HIL framework. Notice that in this case longer simulation time is expected as the entire system is running in real-time.

C.5.2 Validation of Distributed Online Voltage Coordination

This section addresses the validation of distributed online voltage coordination concept by considering selected cases from the work done in [16].

Test Cases for Validating Online Voltage Coordination

Two options for online coordination were considered in [16]:

- Updating the voltage droop values
- Updating the voltage set-point of the ReGen plants

However, it was ascertained in [16] that updating the droop settings according to the actual operating point of ReGen plants did not significantly reduce the power losses within the distribution grid, while updating the voltage set-points according to the actual operating point of ReGen plants reduced the power losses within the distribution grid to a measurable extent. Moreover, it decreased the reactive power utilization rate of the ReGen plants, in comparison to distributed off-line coordination in [16]. Therefore, this paper only considers the case of updating voltage set-points of the ReGen plants.

In [16], four different update rates (10 s, 1 min, 5 min, and 15 min) were considered in simulations for adjusting the voltage set-point of each ReGen plant to evaluate their impact on the power losses within the grid. Since it has already been shown in Section C.5 that the non-RT communication model performs the same as the RT communication setup (with KauNet), two update rates are considered as test cases to validate the non-RT simulations via RT setup i.e., 10 s and 1 min. Further, as in [16], a time frame of one hour is considered sufficient to represent a volatile power profile covering the extreme operational points at high wind speed and solar irradiation.

Test Results

Figure C.14 shows, for each ReGen plant in the BDG, the active power (P), reactive power (Q) and voltage (V) profile both for non-RT simulation and RT communication setup throughout the considered time-frame of 1 h according to the specified test cases. It can be observed in Figure C.14 that no significant differences are observed for the specified test cases in the RT test setup as compared to the non-RT tests. However, since there is a little difference seen in the some results, it is worth calculating the percentage error in each case. The percentage error in case of V and P is calculated based on the difference between non-RT and RT results, keeping non-RT results as reference (see Equation (C.1)). The same applies for P, while, for Q, it can be observed that the signal includes zero, which will give infinitely large errors once divided by the reference signal (non-RT). Therefore, for Q, a delta signal (ΔQ) is plotted which is the difference between the Q obtained by both the setups i.e., non-RT and RT (see Equation (C.2)). The results based on Equations (C.1) and (C.2) are shown in Figure C.15.

$$Error[\%] = \frac{V_{nonRT} - V_{RT}}{V_{nonRT}} \times 100 \tag{C.1}$$

$$\Delta Q = Q_{nonRT} - Q_{RT} \tag{C.2}$$

Results Discussion and Summary

As discussed in Section C.4, to reduce the grid power losses being raised by reactive power compensation, the voltage set-points of individual ReGen plants should be updated in regular intervals with an update rate of reference signals to be in the time interval of 10 s to few minutes. With these recommendations, the authors have elaborated on the impact of using general-purpose public network communication infrastructure on on-line voltage control coordination in [7]. Communication aspects related to the network infrastructure and related protocols were evaluated in [7] with respect to the related latency and validity of the signals being exchanged between Aggregator and ReGen plants, resulting in deviating voltage control performance in the distribution grid. However, it was ascertained in [7] that, with an update rate in the range of seconds to minutes (10 s–15 min), latencies incurred by using those public networks do not affect the delivery and coordination of voltage service with respect to stable voltage profile management.

The results obtained in Figure C.14 confirm that the exchange of V, P and Q from all ReGen plants via RT-HIL setup are approximately the same as those obtained via non RT setup. This clearly indicates that the resulting power losses calculated based on the signals obtained via non RT setup will also remain the same in the current RT-HIL setup. However, a collective error of less than 1% approximately has been observed in Figure C.15 which could be imposed by the Ethernet or other real-time effects in the link. Moreover, the relatively higher error seen initially in each case is expected due to the HIL initialization setup, which requires a detailed sensitivity analysis for this setup in the future.

Challenges in HIL Setup and Future Directions

Although HIL-based simulations offer a wide range of possibilities for testing and validation of SG solutions (one of which is described in this paper), there are several faults and challenges that may restrict its operation (see Section C.5.1). For instance, the transient values in Figure C.15 show relatively higher errors that suggest some unexpected operations due to the HIL initialization setup. This initial higher error (and even the <1% error for rest of the test case) might not be significant enough to make any difference for time frame of one-hour. However, for the tests with longer durations, these errors may not always be easy to handle, especially in the case of RT HIL setup while taking into account the impact of ICT. For an ICT based HIL validation process, it is crucial to ensure a synchronous data flow among each component, along with the concurrency of simulators in use. These synchronous data flows are required for both software-to-software and software-to-hardware interfaces [37]. Moreover, when it involves the co-simulation of power system and communication network for an integrated analysis of both domains, it is necessary to synchronize both simulation tools properly at runtime.

Secondly, one of the most important considerations while carrying out HIL based simulations with power system interface is the closed-loop stability. The occurrence of any instability may not only lead to erroneous results but can also cause expensive damage to testing facilities, controllers and other hardware under test [37]. According to Ren et al. [37], the natural inaccuracies, for instance time delay, limited bandwidth, harmonic injections of the interface amplifier, etc., make a power HIL simulation prone to instability. For high power applications, these instabilities can even be more severe. Therefore, understanding and addressing the different types of errors/faults as well as the causes of instabilities is mandatory, so that the RT-HIL framework can be applied as a reliable testing system. This requires a detailed sensitivity analysis along with the fault analysis for the current setup in the future.

C.6 Conclusions

The main goal of this paper is to validate coordinated online voltage control algorithms via RT-HIL framework that were proposed in previous publications. A model based design approach in SGs has also been introduced as an important methodology in the design and implementation of SG technologies, solutions and corresponding products. Based on this approach, the paper addressed the validation of the proposed ICT model for off-line studies. The proposed ICT model is verified and validated through different test cases against the complete network model and related data traffic implemented in the SES Lab. It has been shown that the performance and characteristics of the non-RT ICT model matches with the detailed RT-HIL model. However, the non-RT model should be used for preliminary control studies, while, for validation purposes, the detailed RT-HIL model should be used to achieve a high TRL. Further, the validation of coordinated online voltage control for ReGen plants in MV grids is achieved. Two test cases, based on the results from validation of the ICT model as well as the main findings in previous publication were implemented in the RT-HIL setup. Deviations below 1% were obtained for the main variables involved from both off-line and RT studies. These results confirm that the main assumptions regarding ICT behavior considered in previous studies are valid.

The proposed methodology offers a systematic approach in tuning and design of voltage control coordination applicable in distribution grids with high penetration of ReGen plants. Classical control design and reliable operation of distribution grids are combined with ICT aspects that are of crucial importance in these applications. The presented MBD approach not only simplifies but also shortens the time-to-market for SG applications. Thus, confidence in new control approaches along with high TRLs (up to 6) can be obtained in early stages of the development with realistic emulation of real power grid and communication networks including the respective data traffic. The proposed method will ultimately support the DSOs in stability and security of the power supply.

As part of future activities, the network parameters such as packet loss rates, delay components and various update rates along with the laboratory hardware will be considered for sensitivity analysis. Moreover, validation of the following ancillary services from ReGen plants will be considered: **(1)** frequency restoration reserve (FRR, also known as secondary control) using a detailed model of the power grid e.g., modified 12-bus systems; and **(2)** frequency containment reserve (FCR, also known as primary control).

Acknowledgments

This work was carried out by the Department of Electronic Systems in cooperation with the Department of Energy Technology at AAU. Energinet.dk is acknowledged for funding this project in contract number: PSO project 2015 No. 12347, "Ancillary Services from Renewable Power Plants (RePlan)", `www.replanproject.dk`. University of the Punjab, Pakistan is acknowledged for funding the PhD of Author 1 (Kamal Shahid).

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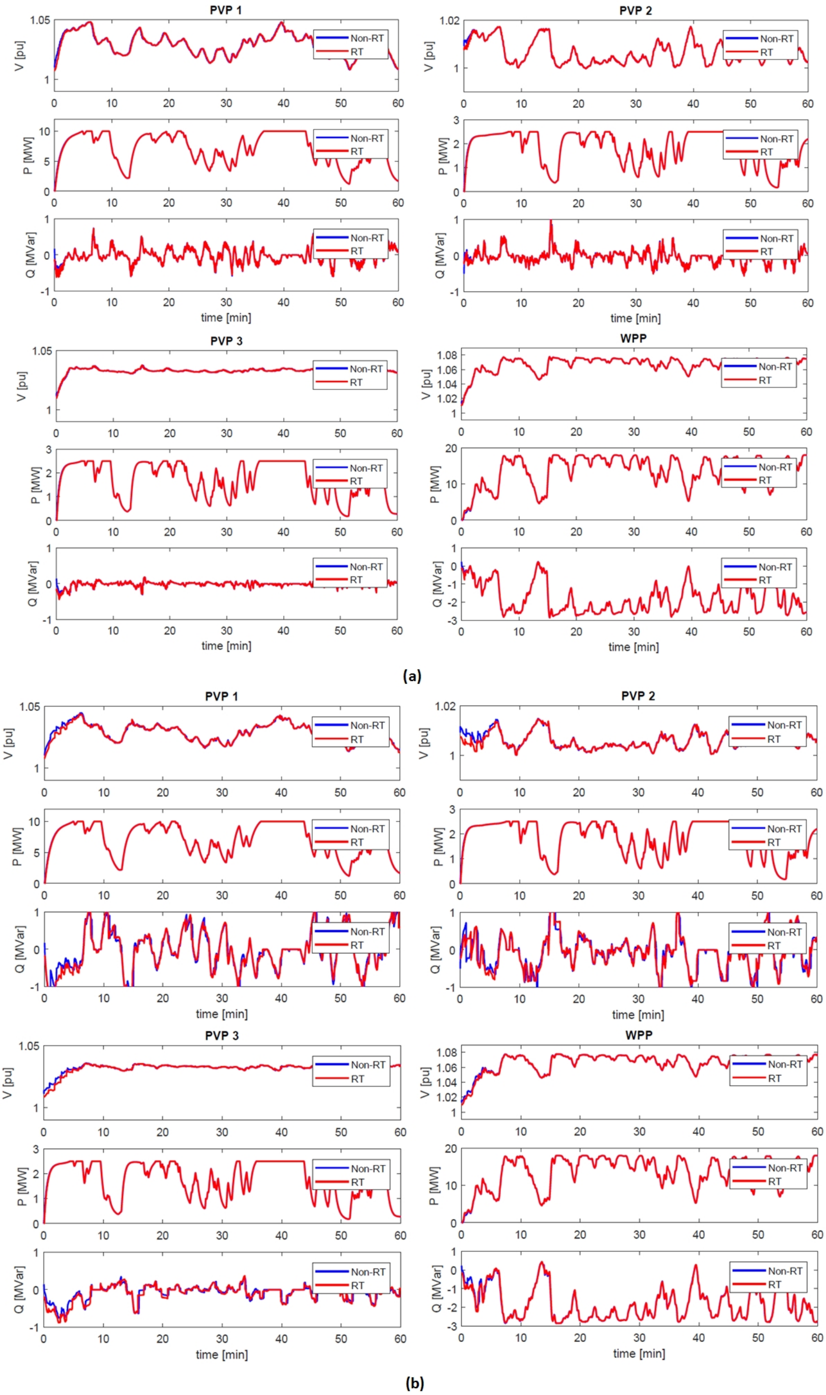

Fig. C.14: P, Q, V of PVP 1, PVP 2, PVP 3 and WPP over one hour for: (**a**) 10 s update rate; and (**b**) 1 min update rate.

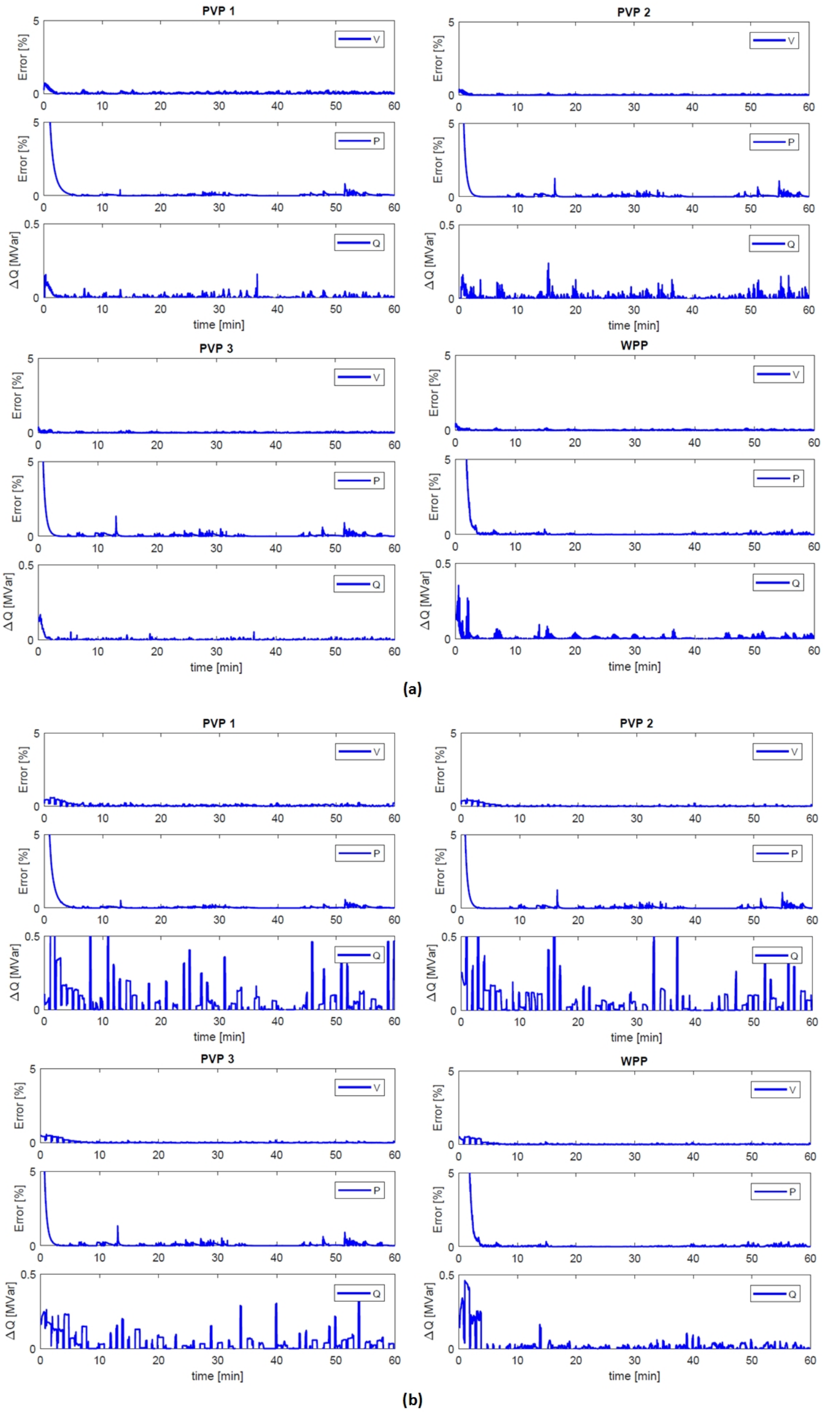

Fig. C.15: Error in V, P and Q of PVP 1, PVP 2, PVP 3 and WPP sent via non-RT and RT communication models over one hour with: (**a**) 10 s update rate; and (**b**) 1 min update rate.

Paper D

ICT based Performance Evaluation of Primary Frequency Control Support and Coordination from ReGen Plants in Smart Grids.

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Abstract

The increased penetration of renewable energy generation (ReGen) plants in future power systems poses several challenges to the stability of the entire system. In future green energy rich power system, the responsibility for providing ancillary services will be shifted from conventional power plants towards ReGen plants, such as wind and photovoltaic power plants. Frequency control support from the wind power plants (WPPs) is one of the crucial ancillary services in order to preserve operational stability in case of grid disturbances. Among other requirements, the ability to provide fast frequency control support from ReGen plants will highly depend on the underlying communication infrastructure that allows an exchange of information between different ReGen plants and the control centers. This paper, therefore, focuses on the impact of communication and the related aspects to provide online frequency control support from ReGen (with special focus on WPP). The study is conducted with an aggregated WPP model, integrated into a generic power system model, specifically designed to assess the ancillary services in a relatively simple yet relevant environment. Various case studies with different wind speeds at a particular wind-power penetration level and communication scenarios are considered to evaluate the performance of power system frequency response. The article provides the transmission system operator (TSO) and other communication engineers insights into the importance and various aspects of communication infrastructure for general service coordination between WPPs and specifically primary frequency control coordination from WPPs in future power systems.

D.1 Introduction

The trend in power systems all over the world is changing and expanding through new interconnections with large penetration of ReGen plants, such as, WPP and photovoltaic power plants (PVP). This trend in future power systems not only adds to their complexity but also make these systems more vulnerable and dependent on production from Renewable Energy Sources (RES). Conventional power plants are also expected to be replaced by ReGen plants. For instance, at national level, Denmark has set goals to reach 100% renewable energy by 2050 [29]. Other countries like USA, China, Norway, Iceland etc. are heavily investing on RES [74]. In addition to the several economic and environmental related benefits, the huge penetration of RES raises concerns regarding operational stability and security of the future power systems [31] due to the fluctuating nature of these energy sources. According to [31, 57, 58], one way to ensure that these ReGen plants will not be detrimental to the stability and security of power systems is to require control functionalities (such as, reactive/reactive power support etc.) from ReGen plants. These control functionalities, also called Ancillary Services

(AS), should resemble to those traditionally offered by conventional power plants. Therefore, in the last one decade, this concern has led the industry as well as academia to an intensified research for developing control algorithms and defining requirements for the provision of AS from ReGen plants (see [8, 10, 19, 21–23, 26, 28, 30, 33, 44, 47, 54, 62, 65, 66] etc.).

The authors in [56–58] have identified voltage stability challenges related to the huge penetration of ReGen plants into MV distribution systems. Further, controllers have also been developed with the specific aim of regulating the voltage/reactive power and analyze the suitability for a coordinated voltage stability support AS from WPPs and PVPs in distribution levels. However, this paper focuses on the provision of frequency stability support AS from ReGen (especially WPPs). According to [31, 37], the capabilities (technical as well as operational) of WPPs to provide frequency control support can be confirmed from most of the available research in this area. For instance, the provision of frequency stability support with regards to inertia and primary frequency control has been investigated in [19, 23, 30, 44, 47, 54, 62, 65], while [8, 21, 22, 26, 28] focus on the small-signal stability support as the damping of power oscillations. Regarding the provision of AS from WPP, initially individual wind turbines remained in focus to investigate their capabilities to provide a required AS. (see [9, 23, 34, 36, 47, 49, 54, 65]), however now in the recent years, the focus of research has shifted towards investigating provision of AS at "plant" level (see for instance [8, 15, 16, 20–22, 26, 28, 30, 32, 53, 64]).

It should be noted that despite of a lot of work (as cited above) on the provision of AS from ReGen plants, an essential aspect scarcely addressed in recent years is related to the role of Information and Communication Technologies (ICT) in the provision of online AS. The provision of online ASs (such as voltage/ frequency control support etc.) highly depends on the underlying communication network infrastructure. Therefore, the performance and characteristics of ICT related issues have to be considered appropriately during the design and assessment any AS from ReGen plants, as this might affect the provision of AS from ReGen plants and ultimately to the overall power system.

In [60, 61], the authors have investigated the impact providing online voltage/ reactive-power support from ReGen plants using cellular based public networks. It has also been identified how higher delays, failure in communication and cyberattacks can deteriorate the performance of a power system. Regarding communication impact and its requirements for frequency control, most of the work has been done in relation to the load frequency control (LFC) from the conventional power plants. Such as, the authors in [13, 14, 42, 72, 73] have addressed the issue of delays in communication for LFC using linear matrix inequality technique, the robust decentralized method and PI type controller. Reference [14] shows how communication delay effects LFC in a deregulated environment. Furthermore, [63] reported time delay in design of LFC in deregulated environment. The authors in [52] have explored the effects of including communication delays on the small signal stability of power systems. Whereas, [41, 71] proposed methods to remove oscillations that occur as a result of time-delayed feedback control in power systems. The estimation of communication delay for LFC in two-area power system is described in [59], yet, without considering the RES integration into the power system. Similarly, [59] proposes a method to thwart time-delay switch attacks on LFC in distributed power systems without taking into account the power production from RES.

Therefore, in this paper we assess the impact of ICT on the frequency control support (Fast Frequency Response (FFR)) from ReGen plants, with special focus on WPPs. It is pertinent to mention here that instead of relying on assumptions regarding delays or packet loss rates, considerations on delays in communication network models are based on real measurements. A coordination scheme for FFR including parameters as proposed in [12] is considered for analysis. Further, two operating conditions of WPPs are taken into consideration namely partial and full load, respectively.

The scope of this article is not to study control coordination, design FFR controller or make a perfect match between control response and communication delay to find optimum parameters. However, the main goal and scope of this article is to demonstrate the ICT related aspects, challenges and requirements associated to a given frequency control support scheme from WPPs. The design of FFR controller and its parameter tuning has already been addressed in [12] and adopted as such in this paper. While, for the ICT part, cellular communication networks are considered for their ubiquitous coverage around the globe. Further, it could be a remarkable achievement to assess the entire European grid through simulation studies. Nevertheless, the necessary level of information related to the entire EU grid system is not available for the academia. Therefore, by studying a small but representative power system, having the same characteristics and properties as that of the continental European system, will be more practicable given that the proposed solutions are scalable and replicable. For this, a generic island power system model developed and used in [12] has been used to generate relevant case studies. Although this generic power system model has been designed to be used with various wind power penetration scenarios [12], this paper only considers a penetration level of 50% (to comply with Denmark's intermediate goal for 2020 [29]). Moreover, a perfect knowledge of instantaneous available wind power has also been assumed for the test cases. The work presented in this article is believed to provide the TSOs with new insights into the role, need and importance of communication networks for the provision of AS from WPPs in power systems where conventional power plants are being largely displaced by WPPs.

The paper is organized as follows: Section D.2 elaborates on the various aspects and challenges associated to ICT in providing online frequency support and coordination from ReGen. Section D.3 defines the use case and test scenarios, while the evaluation criteria for assess system frequency is stated in Section D.4. The evaluation setup including the description of the power system model and test cases are discussed in Section D.5. Section D.6 presents the results related to the impact of communication properties on online frequency control coordination and finally the conclusive remarks are reported in Section D.7.

D.2 Online Frequency Support and Need for Communication

According to [45], "Frequency stability refers to the ability of a power system to maintain steady frequency following a severe disturbance between generation and load". Frequency instability can result in continuous frequency swings that leads to the tripping of generating units or loads. During the changes in system frequency, characteristic times of the actuated processes and devices range from milliseconds (like under frequency control) to several minutes, corresponding to the response of devices.

Frequency control support and coordination from ReGen plants is reported in [12], including the related models, methodologies, development of controls and study cases considered for both primary and secondary frequency control. The focus in [12] was to improve the frequency control support from ReGen plants (with special focus on wind power plants) by optimizing and coordinating the total support from ReGen plants. In traditional power system operation, primary frequency control has been performed in the conventional power plants at the plant level. Moreover, in the literature, the WPPs that are employed with inertial response, fast frequency control, or enhanced frequency response, are investigated similar to the traditional approach. In this paper, possible aggregator level is proposed for frequency support mechanism in the future power system systems with high wind power penetration and fast communication networks. A similar concept has been investigated and some implementation was done in [3]. According to [12], the provision of frequency support in power systems is usually based on the measurements of frequency deviation and rate of change of frequency. The measurements of frequency deviation are quick and reliable, however measuring the rate of change of frequency is done over sliding windows of several hundred milliseconds and is thus always afflicted with a delay. For the online coordination, ReGen plants should send status updates at regular intervals to the system operator, based on which set-points are calculated and sent back to the ReGen plants (see Figure D.1). Since, the ReGen plants will be dispersed geographically throughout the system, and being far apart from the control centers, a time delay is expected in receiving the set-points. As a result, the contribution of a ReGen plant to the system frequency support will be also be delayed. The delay as well as other properties of communication (such as packet loss, throughput etc.) associated to any communication network depend on the underlying network communication infrastructure. Thus, the optimized FFR support discussed in [12] will likely be non-optimum, if not deteriorating to the system response.

Therefore, in the following subsections, this paper highlights: **(1)** the different communication network options that can be used in the future to support communication between ReGen plants and the control centers, and **(2)** the extent to which the delays associated to these networks can impact frequency support coordination from ReGen plants. The optimization process employed in [12] is used as such including the various delays in measurement and communication.

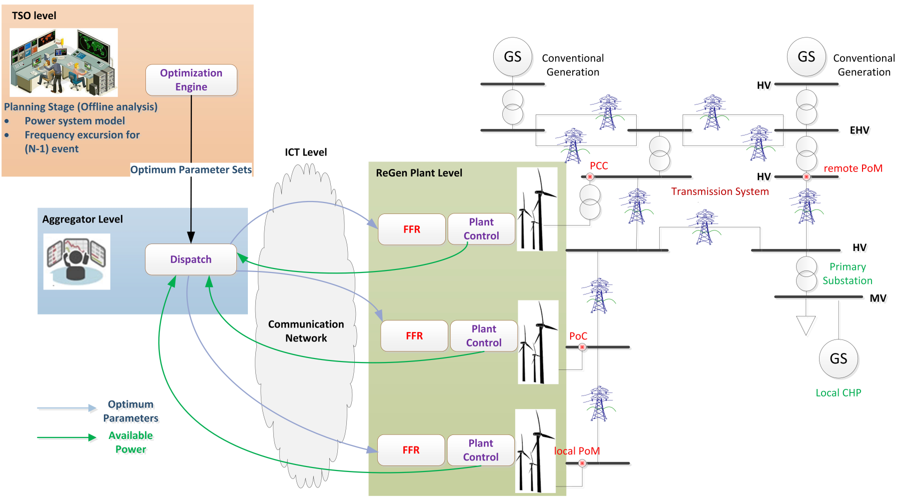


Fig. D.1: Implementation of Offline Optimization Approach with Control Levels.

D.2.1 ICT Challenges in Online Frequency Support

Compared to voltage/reactive-power, which is more of a local phenomenon [25], the LFC is a global phenomenon that has been implemented in a centralized scheme since the start of the interconnected power system [25]. Therefore, when it comes to provide frequency support and coordination from power generation plants, the TSO directly takes the charge [12]. However, it is also foreseen that aggregators of these ReGen units may take the responsibility, in close cooperation with system operators (TSO/DSO), for hosting ancillary services, such as voltage/frequency control capabilities, besides trading energy [38]. Nevertheless, in any case, it will be essential to add Supervisory Control and Data Acquisition (SCADA) with an appropriate communication network infrastructure to connect ReGen plants to system operator.

Nowadays, since fiber optics, cable Internet, and cellular networks are already widely deployed by the telecom operators and have high geographical coverage [6, 27], these technologies could be used to connect ReGen plants to the control centers using SCADA. Communication via fiber optics offers several advantages over copper as well as other modes of communication, such as: super low latency, prevents electrical noise induction, and eliminates signal ground loops [11, 55] etc. However, for wide-area SCADA network, installing fiber optic cables requires huge initial investment and thus, highly expensive. In this regards, wireless networks prove to be a cost-effective substitute to the use of fiber optic based communication. Wireless networks, specifically cellular networks, can provide up to 90% savings [70] compared to installing fiber optic cables, with significantly accelerated implementation. Today, cellular networks have turned out to be a dominant means of communication for Machine-to-Machine (M2M) communication in not only smart grids but also other control systems. For instance, according to [7], "Victoria's South East Water replaced its digital radio system with a high-speed IP-based communications hub with 3G and 4G cellular modems, as well as DSL direct links". Therefore, in this paper we focus mainly on using the cellular networks for communication between the ReGen plants and the control center to demonstrate the impact on the provision of frequency control support from, specifically, WPP.

D.2.2 Role of Communication Networks in SCADA

As the name implies, SCADA system provides the control and monitoring of remote devices (called Remote Terminal Units (RTUs)) through an appropriate communication infrastructure. It uses communication protocols such as Modbus or DNP3 that are based on polling schemes for collecting information from all end devices and reporting the data back to a central SCADA master [17]. Based on the received data, the system can then send set-points or control decisions accordingly. Since, SCADA was initially designed for industrial processes using proprietary serial protocols; it was usually kept isolated from not only other networks but also the computer systems [17]. However, in order to merge many different network types (such as data, control signals etc.) in a single network as well as to present significant cost savings to a business, SCADA industrial control systems are now being connected with cooperate networks on the internet. With this, the traditional SCADA has shifted from the proprietary serial protocols to the world of Internet Protocol (IP). Today, many industries have increased connectivity between corporate network and SCADA to allow more informed decisions to be made and thus improving businesses. It is important to mention here that moving from proprietary networks to IP-based networks increases the level of risk [17] in terms of cyber-security etc. Therefore, with increasing interest in the security of Networked Control Systems (NCS) such as smart grids, it becomes vital for the asset owners to understand the various available IP-based solutions and make an effective security based risk management decision [17].

DNP3 and Modbus were originally designed and aimed for use in communication links supporting serial data communications with low-bandwidth requirements. Therefore, these data collection applications in SCADA were tolerant of long communication latencies with most likely deterministic delays due to direct link between application layer and MAC layer. On the other hand, since IP-based data links (wireless as well as wired Ethernet bases networks) offer higher data rates, the IP-based SCADA allows for lower communications latency, with naturally stochastic delay types. It is worth to mention here that the latency related requirements for each SCADA scheme are determined by not only the number of devices being polled, but also the rate at which these devices are required to be polled relative to control system response time requirements [17]. While, high throughput wireless networks are more flexible in terms of network size as well as polling rates. Thus, based on the available throughput, trade-off in the network size can be made during the design phase to attain a desired response time based on the given data rate

Today, the cellular technologies (such as, 3G, 4G, LTE) provide throughput on the order of millions of bits per second. Additionally, cellular communications network and base station infrastructure being ubiquitous, allows greater system access and easy scalability. This means that a large number of end devices can be polled with unbounded network size. Further, in cellular networks, a given area is divided into distinct cells, where each cell is connected to the wireless transceiver. All cells in the given area are interconnected to cover long distances, providing high data speeds, low initial costs and several other significant benefits over other forms of wireless communication. However, the technology used in any considered network scenario, will have an important impact on the costs of the actions in the operational processes and thus, also on the overall Operational Expenditure (OPEX) cost for the considered scenario. From the perspective of a system operator (i.e. TSO), to employ cellular networks, an exhaustive techno-economic model for these networks (as well as individual technologies) with inherent coupling of Capital Expenditure (CAPEX) and OPEX cost elements is required. Such a model for LTE networks is provided in [43], while [69] describes a general model for OPEX of a telecom operator.

From the perspective of reliable and fast delivery of any ancillary service from ReGen, it is important also to analyze the performance of these cellular networks based on the critical communication properties. Therefore, in the following, coverage and performance of cellular networks in Denmark is briefly described.

D.2.3 Cellular Network Performance in Denmark

Although many communication properties, as detailed in [40, 46, 55], can be linked, but two properties are considered here, i.e. delay and information loss rate (also termed as packet loss rate). Because, delay in transmission can cause the operator to make decision based on old data, or a ReGen to change behavior based on old control messages. While, information loss in communication might mean that operator/ReGen tries to make decision based on incomplete data. Since the delay and packet loss in cellular networks are non-deterministic, it is worth exploring the exact range of these properties for analyzing the impact of using these networks to support frequency control and coordination from ReGen. In the following, the range of delays and packet loss probabilities is discussed, specifically for Denmark.

Information Collection and Description

NetMap [5, 51] is used to obtain information about cellular technologies and their performance in terms of Round Trip-Times (RTTs) and measured signal strength [48]. NetMap is a crowd sourcing based system for performing and collecting measurements of cellular network connection performance. NetMap is exploiting the ubiquity of smartphones by having them perform and collect measurements of network performance using the cellular connection. This is done by having users install an app on their smartphones, acting as front-end client software, which handles the measurements and scheduling. The collected measurements are then submitted to the back end system, where measurements are collected and processed. NetMap is currently only deployed and measuring cellular networks in Denmark [5].

Measurement scenario

To understand the measurement results it is important to understand what is being measured. The NetMap setup consists of a front-end component and a back end component where the connection between is measured. The front-end component is an app on a smartphone with a cellular connection, and the back end component is a fixed measurement server, connected to the research network in Denmark. This means that the connection covers two types of connections: **1)** the wireless cellular connection to the radio access network, and **2)** the connection between radio access network and measurement server.

The assumption is that the main influence to the network performance origins from the cellular connection in terms of delay and variance.

In Denmark there are three cellular networks (in reality four but two of them share cellular network resources) [2]. The three networks (referred to as A, B and C in Figure D.2 and Figure D.3) are connected to the same internet exchange point, Danish Internet Exchange (DIX) [2]. The measurement server is connected to the Danish research network, which also is connected DIX. This means that the performance of the different ISP networks can be compared because the measurements only differ in which ISP wireless and internal network they are performed on. The devices that perform the measurements are regular consumer smart-phones, which means that there are many factors that influence measurements. For instance, different applications on the devices consuming resources and utilizing the connection, as well as the mobility of measuring devices.

The measurements that are used in this context are RTT and signal strength measurements. RTT is measured using both UDP and TCP. A request packet is sent to the server that replies as fast as possible. The time between the request and the reply packets is logged as the RTT. Request/reply sequences are not overlapping and for TCP the connection handshake is done before the measurement is initiated. NetMap performs a set of measurements periodically, and for each period 20 RTT request/reply sequences are performed. The signal strength is logged for the currently active connection after the RTT measurement is done.

In the following, measurements from the three different ISP networks are presented, based on 2G, 3G and 4G technologies. These measurements are based on packet loss and RTT measured using several devices. The measurements are based on around 683000 RTT measurement sequences at different distances/locations of the end devices from the communication masts of different ISPs, capturing almost entire Denmark (for details, see [5]). These measurements have been obtained over a period of one and a half year with varying number of end devices. Figure D.2 summarizes the results of RTT measurements from the three ISPs (based on 2G, 3G and 4G technologies) in terms of Cumulative Distribution Function (CDF) i.e. probability that RTT takes a value less than or equal to a certain range of time in milliseconds. While Figure D.3 shows the number of packets sent using three ISPs along with the packet drop probabilities in each case.

These NetMap based measurements are highly useful as they provide realistic performance under realistic conditions from networks that are normally hard to obtain information from/about, and are relevant for e.g. operators (such as TSO) to assess their possibility to provide connectivity service to control systems. These measurements patterns have been used in testing the provision of online frequency control support service from WPPs. (See Section D.5.3).

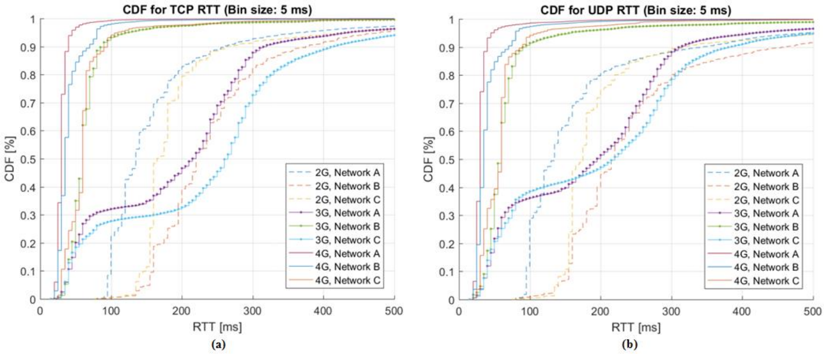


Fig. D.2: RTTs measured for **(a)** TCP and **(b)** UDP based packets using three cellular networks in Denmark.

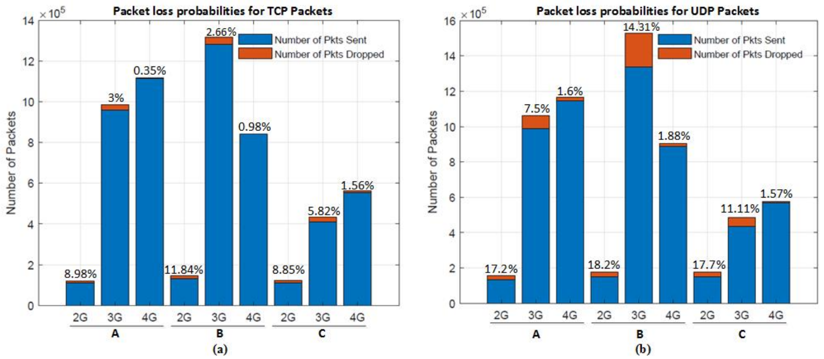


Fig. D.3: Packet loss probabilities measured for **(a)** TCP and **(b)** UDP based packets using three cellular networks in Denmark.

D.3 Use Case and Test Scenarios

This section presents the considerations and assumptions made related to the use case and test scenarios in this paper.

As a part of power production from ReGen plants, only WPP generation is considered. The contribution from other renewable sources (such as PVP) is also important; however, it is left for future research. (Note: In Denmark, out of the total generation capacity, wind energy is around 43%, while that from PVP is around 3% (to date) [4]. The rest of power generation is contributed from steam, hydro and nuclear power plants, respectively.). For this paper, the wind power penetration is set to contribute 50% of the total generation. Although the power system model used in this paper can be evaluated for various wind power penetration levels, but this assumption is specifically made to comply with Denmark's mid-term goal to achieve 50% power production from RES [29]. (For more details of 50% wind power penetration level, see Section D.5.1)

The real power system in Denmark does not consist of a single WPP [4]. Similarly, around the globe, depending on the system size, there are several WPPs connected to the grid and operate at different operating conditions as the prevailing wind speed varies geographically. It is therefore valuable to investigate how combined frequency support from multiple WPPs performs under varying network conditions. For this reason, there are three WPPs connected to the power system. These WPPs are divided into offshore and onshore WPPs. Based on the size of a WPP, the onshore WPPs are further subdivided into two groups. These groups depict the future Danish power system with major contribution from wind power plants of different sizes. The three WPP groups are assumed to have equal share of power generation, see Table D.1:

Table D.1: Size and Share of three WPPs connected to the Power System.

WPP Type	Size	Size in MW	Contribution [%]
Offshore	Large	Above 100	33
Onshore	Medium	50 - 100	33
Onshore	Small	<25 -<50	33

When kinetic energy of a wind turbine is used, there can be a reduced active power output at the recovery period depending on the wind speed [66]. According to [67], Denmark is one of the major areas in European communities that have a high wind energy resource. However, in a small country like Denmark, the wind speeds tend to be almost the same throughout its territory, while in larger interconnected systems varying wind speeds can occur in different parts [1, 67]. Therefore, from the range of wind speed distribution found in Denmark [35], two instantaneous wind speeds (7 and 14 m/s) are selected to test the impact of communication on frequency control support from WPPs. Choosing these wind speeds will cover a large part of a typical wind speed distribution found in Denmark [35]. Here, 7 m/s is the wind speed corresponding to partial loads in the WT, while 14 m/s wind speed corresponds to full loading (full power production). Hence, the results of this paper will be applicable over a wide range of operating points encountered during the normal operation of WPPs in Northern Europe.

It is also pertinent to mention here that the tests cases in this paper are based on the assumption that all WPPs are operating under the same wind regimes (i.e. all WPPs are experiencing the same wind speed at a time). However, as a part of future research, the impact of ICT on frequency control coordination from WPP with non-uniform wind speeds will be explored. Table D.2 shows the two wind speeds based test cases for both onshore and offshore WPPs.

Table D.2: Wind Speeds for Test Cases.

	Wind Power Plants		
	Offshore	**Onshore (Medium)**	**Onshore (Small)**
Wind Speed (m/s)	7	7	7
	14	14	14

While connecting the WPP to a control center, a network can either be private or public. Private networks are fully owned and the cross traffic can be easily managed. In fact, if the only entities allowed on the network are those with time critical data, then in most cases (i.e. cables are not physical cut, the wireless frequency is not directly jammed by external sources etc.) data will be reliably transported fast and efficient with most modern communication technology. However, this is an extremely expensive and inefficient solution. Additional traffic can obviously be put on the network, but the routers in between that take care of the traffic ending at the right address must be able to differentiate between packets, i.e. provide Quality of Service (QoS), which requires configuration and management. Owning the network enables full control of QoS settings but is costly and requires proper manning and expertise to operate and maintain the network. Further, private networks are for security reasons more likely to be standalone, disabling communication and data exchange beyond certain boundaries, which for some applications is a degradation. For instance, remote monitoring or control of systems are often not possible outside control rooms due to physical separations of external networks.

On the other hand, public networks refer to the networks that are operated by e.g. tele-operators or any other third party company or service provider, which has the expertise and manning to operate the network, routers etc. In such networks, internals of the network are not to be taken care of by the end user, thus, can enjoy data being transported from source to destination in most cases at best effort. Only limited possibility to control QoS settings are given if additional money is paid. Tele-operators work with the concept of M2M communication, which allows certain timely and reliability requirements to be satisfied since traffic is internally prioritized effectively for transportation. It is worth to note that it is only the case as long the data traffic stays within boundaries of the given tele-operator. If data goes outside the domain of the tele-operator, then QoS is most likely to be lost, thus, time and packet loss rates cannot be guaranteed. However, public networks are cheap and flexible, but suffer to the extend that these have to be shared among millions of other customers, hence exposes data exchange to stochastic non-controllable delays and packet drops.

Since the size of offshore WPPs in this paper is considered to be above 100 MW i.e. large wind power plants, the network connection is set to be private, so that high QoS in terms of fixed deterministic delay as well as other communication properties can be guaranteed. While for the onshore WPPs, both private as well as public network connections are considered in the test cases. Furthermore, as an ideal case, a test scenario with all private connections is considered to guarantee high QoS in communication. (see Table D.3).

Table D.3: Test Scenarios based on Network Connections

	Wind Power Plants		
	Offshore	Onshore (Medium)	Onshore (Small)
Network Connection	Private	Private	Private
	Private	Private	Public
	Private	Public	Public

D.4 Evaluation Criteria – Key Performance Parameter (KPI)

The results of each test scenario will be discussed and evaluated with regards to the following three important frequency metrics for the operation of a power system (see Figure D.4) [12]:

Frequency Nadir (f_{Nadir}) It describes the minimum point reached by the frequency after a disturbance (see Figure D.4). This metric is important as too low values might trigger protection devices. An improved frequency response should therefore increase the frequency nadir, i.e. reduce the maximum frequency deviation. Due to the under-frequency load shedding limits, the value of f_{Nadir} is fixed around 0.8 Hz in systems with 50 Hz operational frequency [10], while it is 0.9 Hz in systems with 60 Hz operational frequency [10].

Time to reach frequency nadir (T_{Nadir}) It is related to the system inertia. The earlier the nadir is reached, the more energy is released directly after the disturbance. It is, therefore, preferable to reduce T_{Nadir} (see Figure D.4), as it can also have an impact on primary and secondary control.

Time to reach steady state frequency ($T_{SteadyState}$) Since the goal of primary frequency control is to contain the frequency to a new steady state after the disturbance and thereby reduce the dynamic part of the response, a quicker return to steady state is favourable. Therefore, an improvement in the frequency support is indicated by a smaller value of $T_{SteadyState}$ (see Figure D.4).

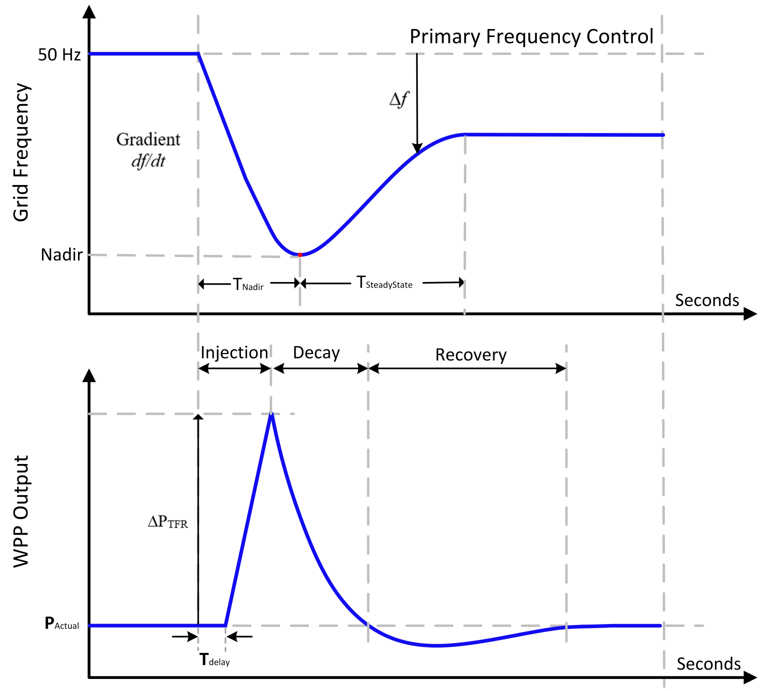


Fig. D.4: Reference frequency and output power shapes of WPP. [12]

D.5 Evaluation Setup and Test Cases

D.5.1 Power System Simulation Model

A generic large-scale power system model described in [12] is used as such to analyze the ICT impact on a coordinated frequency support from WPPs. The frequency control dynamics of a generic large-scale power system are represented as a single-bus model with three WPPs and different types of other conventional power plants, such as steam, hydropower, and nuclear power plants (see Figure D.5). The models of conventional power plants are based on the general purpose governor model, adapted from [18]. The power system is designed to be in balance initially for all test cases, while for testing purposes, a disturbance is introduced at $t = 5 seconds$ in each case. The disturbance is actually introduced by simulating the incidence of power system disturbance on 4^{th} November, 2006 – ENTSO-E for iTesla project [68]. According to [68], on 4^{th} of November 2006, the Union for the Coordination of Transmission of Electricity (UCTE) interconnected European grid was affected by a serious incident originating from the North German transmission grid during night at around 22:10. This incident led to power supply disruptions for more than 15 million European households and a splitting of the UCTE synchronously interconnected network into three areas. This disturbance could have turned into a European-wide blackout but immediate action were taken by all TSOs. However, since this event ranks among the most severe and largest disturbances in Europe [68], it has been considered in this work.

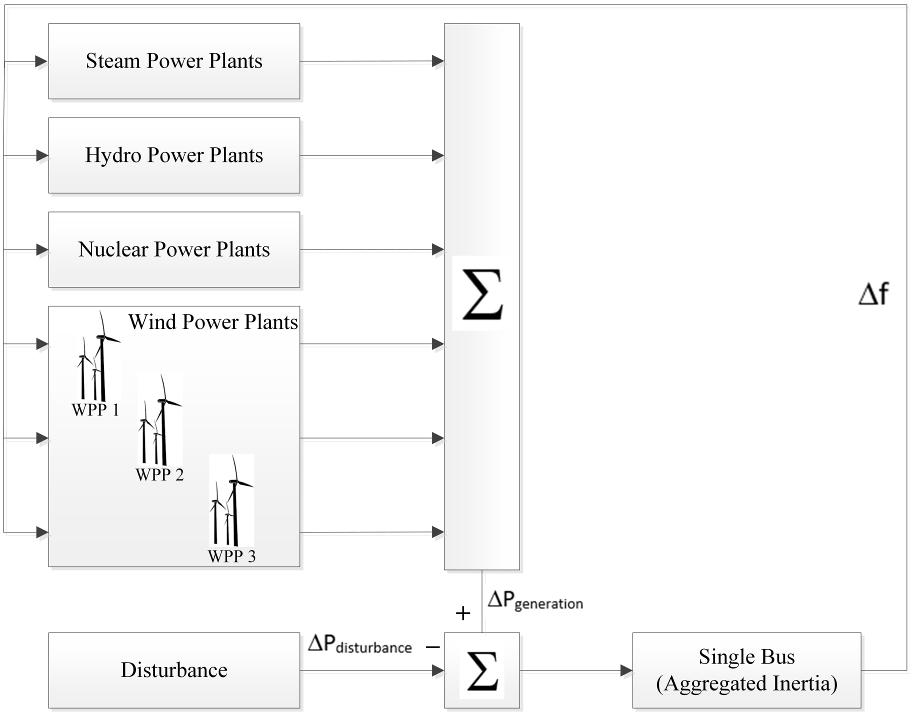


Fig. D.5: Single bus model of large-scale power system model with three aggregated WPPs and other conventional power plants.

In the given system, since the power system is a combination of WPP as well as other types of power plants, the amount of power shared by WPPs will be important factor that has a large impact on the severity of a given load step. The higher the share of wind power, the more synchronous inertia is displaced and the more unstable the system becomes if no further measures are taken [12]. As described in section D.3, for this paper the share from

WPPs is set to be 50% to account for Denmark's mid-term goal regarding renewable energy. In this paper, the wind power share is calculated as follows [12]:

$$WindPowerShare = \frac{WindPowerGeneration}{PeakLoad} \tag{D.1}$$

Here, reference load is the peak load of a given power system, while wind power generation corresponds to 50% of the total load. The various loads adopted in [12] and in this paper for each power generation plant are shown in Table D.4. It is important to note that 50% wind power penetration level is assumed constant for the total wind power in the present study, and only wind speed variations are considered for each wind power plant. This is a conservative assumption; however it can represent the boundaries of the power system operation scenarios such as high load-high wind, low load-low wind, etc. If the wind power penetration depends on the wind speed in the simulations, the wind power penetration will vary for each scenario, which will change the power system frequency profile (i.e. different base cases). Since the aforementioned power system model represents the average frequency and active power deviations, this assumption is reasonable in order to assess the frequency support capability of wind power plants in the presence of the communication infrastructure. It should be noticed that the models and analysis aim the high level performance and investigations for a given power system.

Table D.4: Generation distribution for 50% wind power penetration level

Total Gen. [GW]	**Steam [GW]**	**Hydro [GW]**	**Nuclear [GW]**	**Wind [GW]**
68	25	6	3	34

D.5.2 Communication Network Model

A Communication Network Model (CNM) is added between each WPP and the aggregator control (see Figure D.1), where the aggregator control unit is responsible of calculating and sending the optimal set-point values. The aggregator, CNM and WPP models are shown as three distinct levels in Figure D.6.

Typically, while testing power system models with a communication setup, a fixed transport delay is used to understand network behavior or the impact of delay on information. However, in reality there is much more on top of a simple delay by which a signal might be effected. For instance, as discussed in Section D.2, while considering public networks as a means of coordination

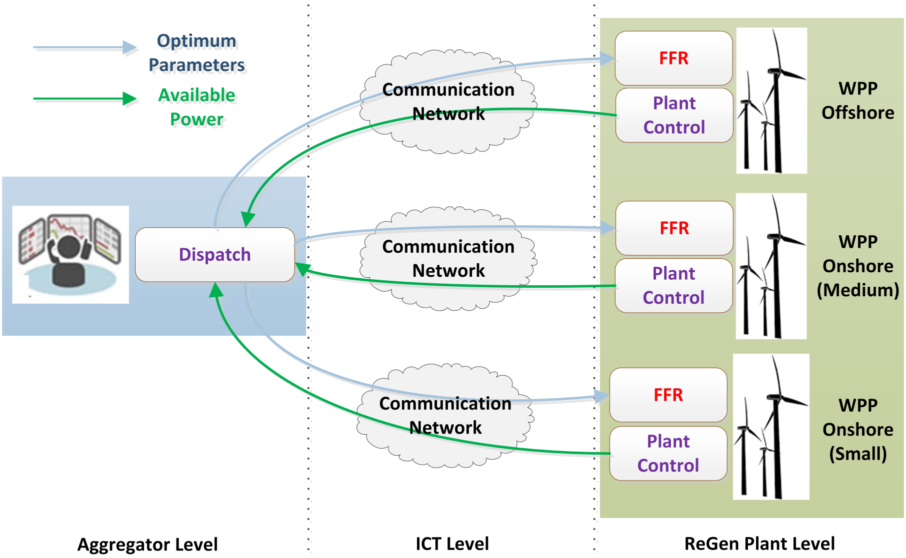


Fig. D.6: Simulation model with ReGen, ICT and aggregator control levels.

between ReGen plants and the system operators, a constant delay or packet loss cannot be guaranteed. It is, therefore, necessary to see how different network conditions (in terms of higher delays or packet drops) affect the performance of a signal. Thus, the communication network(s) shown in Figure D.6 is a network emulator that has been developed in Matlab/Simulink to provide pattern-based network emulation. Figure D.7 shows the CNM used for evaluation of online frequency support from WPPs (for details of this model, see [39]). The patterns that describe the desired changes in the traffic can be created from analytical expressions or traces collected through a real network and are matched with traffic packets to required behavior in time driven mode. As a result, it provides a user with a reasonable estimate of what end-to-end performance can be expected from a communication network. As described in Section D.2.3, the patterns (based on end-to-end delays and packet loss) in this work are based on real measurements obtained using NetMap [50, 51]. It is pertinent to note that since the data was collected via cell phones, it is not what a non-mobile electrical unit would accurately achieve in terms of network performance. However, it gives a reasonable estimate of what an asset can expect in terms of end-to-end performance from a communication network.

Figure D.8 shows a combined histogram of RT-RTT measurements captured from all over Denmark using several devices (see Section D.2.3). Although the measurements were captured for both TCP as well as UDP protocol, but only TCP based measurements are utilized because TCP is used as

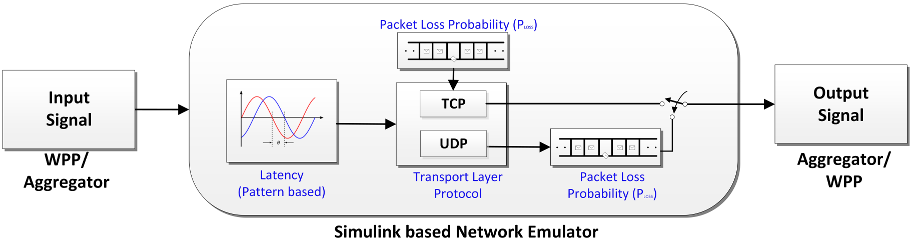


Fig. D.7: CNM used for evaluation of Online Frequency Support from WPPs

a standard transport protocol in almost all industrial applications especially IEC 61850. From Figure D.8, it can be observed that for the maximum cases, RTT lies within the range of 30 ms approximately. This means that a 15 ms delay (half of RTT – assuming the same route for request and reply to/from the server) in the transfer of information update can be expected for the maximum times in daily operations. However, this network being heterogeneous (and shared by a large number of users), the delay continuously varies depending on the network conditions and number of users using the network. For the worst case, the delay is observed as high as 500 ms (RTT).

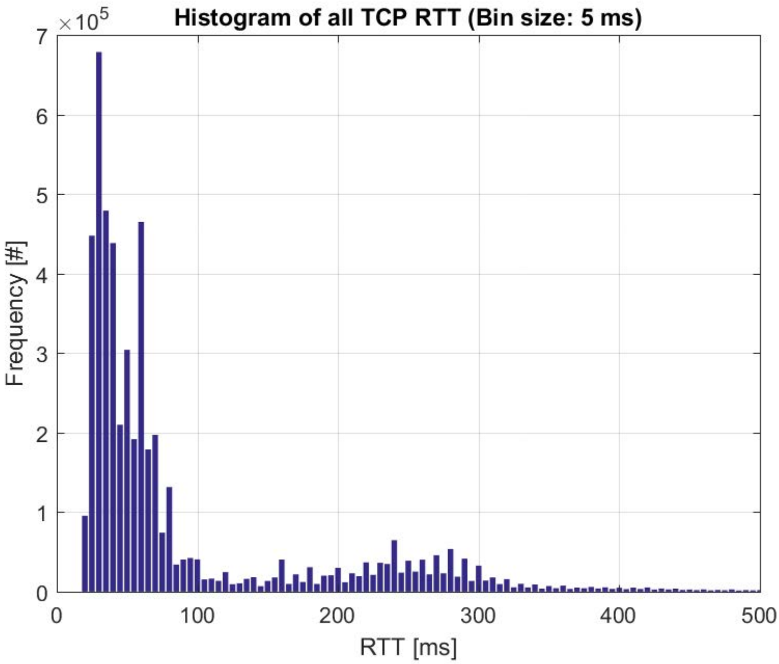
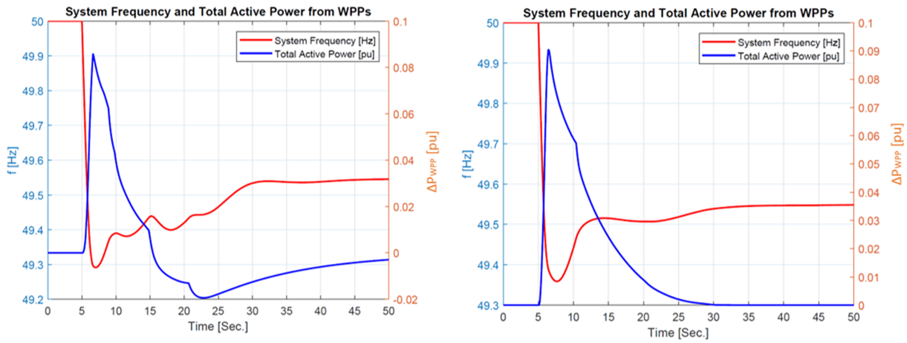


Fig. D.8: Distribution of TCP-RTT traces based on real measurements via NetMap [50]

D.5.3 Reference Scenario for Frequency Response Evaluation

In [12], results related to frequency response and power output of WPPs were obtained through optimized parameters without any communication model. Those results were based on uniform as well as non-uniform wind speeds. However, for this paper, the tests cases are only based on uniform wind speeds (i.e. 7 and $14m/s$, see Section D.3). Therefore, the results based on uniform wind speeds in [12] are considered as reference and used to evaluate the deviation from optimum frequency control coordination due to added latencies.

Figure D.9(a) shows the system frequency and total active power from WPPs for partial loads which corresponds to an average wind speed of $7m/s$, while Figure D.9(b) shows the the system frequency and total active power from WPPs for full loads which corresponds to an average wind speed of $14m/s$.



(a) (b)

Fig. D.9: Reference System Frequency and Total Active Power from WPPs for **(a)** Partial Load (i.e. $7m/s$ average wind speed) and **(b)** Full Load (i.e. $14m/s$ average wind speed).

D.5.4 Test Cases

For each test scenario described in Table D.3, two tests are considered based on the inclusion of a communication network i.e. **a)** with standard communication parameters (specifically delay), and **b)** with higher delays in case of public networks due to cross traffic and/or network congestion etc.

Test Case 1 – Standard Communication As in a private network, there is a full control over the network traffic and a constant delay can be guaranteed, therefore, a fixed standard delay of 10ms is considered. However, in case of public networks, a constant delay cannot be guaranteed (as seen in section D.2), thus the delay traces from a real network are used instead. Combining the results of delay traces obtained from NetMap (see Figure D.8), it can be concluded that the information packet is delayed around 15ms (30ms TCP RTT) for the maximum times.

Test Case 2 – Higher delays For higher delays in communication, three different delays are considered on top of standard communication delays, i.e. 100ms, 500ms and 1sec. to observe the deviation of frequency response from the one obtained from optimum parameters. The one second delay in communication is considered to be the minimum delay that incurs in case of a failure at a communication mast level etc.

D.6 Test Results – Impact of Communication Properties on Online Frequency Control Coordination

In the following, reference system frequency (in Section D.5.3) is compared with those obtained under different delay conditions. This will give an understanding of the extent to which a network delay may affect the system's ability to support frequency control coordination from WPPs.

D.6.1 Test Scenario 1

As in Section D.3, Test Scenario 1 accounts for private connections for all WPPs and evaluated under partial as well as full load (see Table D.5).

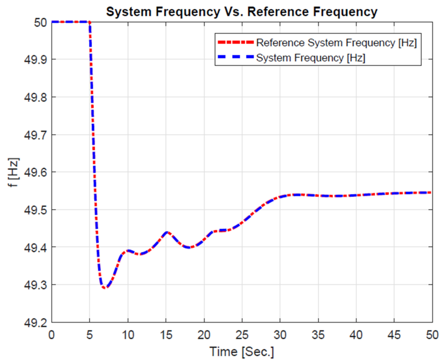
Table D.5: Test Scenario with all Private Network Connections — Ideal Case

	Wind Power Plants		
	Offshore	Onshore (Medium)	Onshore (Small)
Network Connection	Private	Private	Private
Wind Speeds	7 14	7 14	7 14

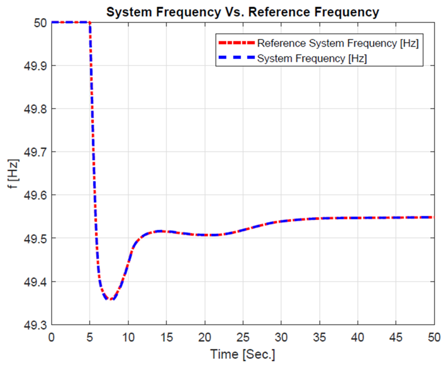
Figure D.10 shows the system frequency (blue) at partial as well as full load after inserting the communication link between the aggregator and WPPs. This current system frequency is compared to the reference system frequency (red) in section D.5.3.

Results Discussion and Summary

Table D.6 provides, for partial load and full load, a comparison of the different values of f_{Nadir}, T_{Nadir} and $T_{SteadyState}$ with the ones obtained from



(a)



(b)

Fig. D.10: System Frequency Compared to the Reference Frequency at **(a)** Partial and **(b)** Full load.

reference frequency response in Section D.5.3. The comparison shown in Table D.6 is further presented in a graphical form in Figure D.11.

Table D.6: Comparison of System Frequency KPIs with that of Reference Frequency

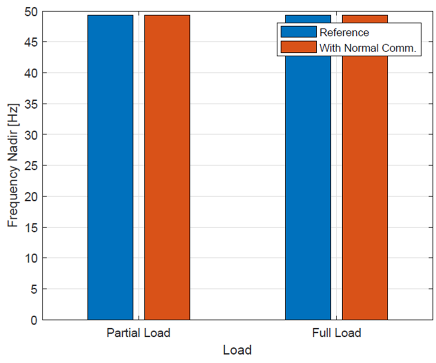
		Test Scenario 1	
		Partial Load	Full Load
Frequency Nadir [Hz]	**Reference**	49.31	49.35
	Normal Comm.	49.31	49.35
T_{Nadir} [Sec.]	**Reference**	6.95	7.618
	Normal Comm.	6.95	7.618
$T_{SteadyState}$ [Sec.]	**Reference**	40	40
	Normal Comm.	40	40

It can be noted that with private network connections between WPPs and control center (aggregator/TSO), all performance metrics match with that of the reference metrics. This implies that private communication networks can prove to be the best source of obtaining optimized/required frequency control coordination from WPPs.

D.6.2 Test Scenario 2

Test scenario 2 accounts for a public network connection for small size on-shore WPP, while private connections for the other two WPPs and evaluated under partial as well as full load (see Table D.7).

Figure D.12(a) and Figure D.13(a) show different system frequency responses at partial and full load, respectively, after inserting the communica-



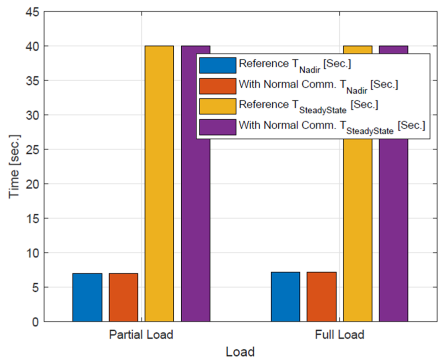


Fig. D.11: Comparison of **(a)** f_{Nadir}, **(b)** T_{Nadir} and $T_{SteadyState}$ with that of Reference Frequency Response.

Table D.7: Test Scenario with Public Network Connection for Small Onshore WPPs

	Wind Power Plants		
	Offshore	Onshore (Medium)	Onshore (Small)
Network Connection	Private	Private	Public
Wind Speeds	7 14	7 14	7 14

tion link between the aggregator and a small share from WPPs (i.e. one-third of the total wind power production). The system frequencies obtained with different network delays are compared with the reference system frequency in section D.5.3. While, Figure D.12(b) and Figure D.13(b) show the total active power of the system at partial and full load, respectively, with different network delays compared with the reference active power in section D.5.3.

Based on the results shown in Figure D.12(a) and Figure D.13(a), it can be concluded that f_{Nadir} decreases with an increase in communication delays, even if a small share of WPPs is connected to the public networks. In case of partial load (Figure D.12(a)), the frequency limit of 0.8 Hz is reached for delays of around $1 second$. While in case of full load (Figure D.13(a)), although f_{Nadir} is decreased by increasing communication delays, however the load shedding limit of 0.8 Hz has not reached for the current setup.

Results Discussion and Summary

Table D.8 provides, for partial load and full load, a comparison of f_{Nadir} as well as T_{Nadir} with the ones obtained from reference frequency response in Section D.5.3 in terms of Δf_{Nadir} and ΔT_{Nadir}, respectively. Where, Δf_{Nadir}

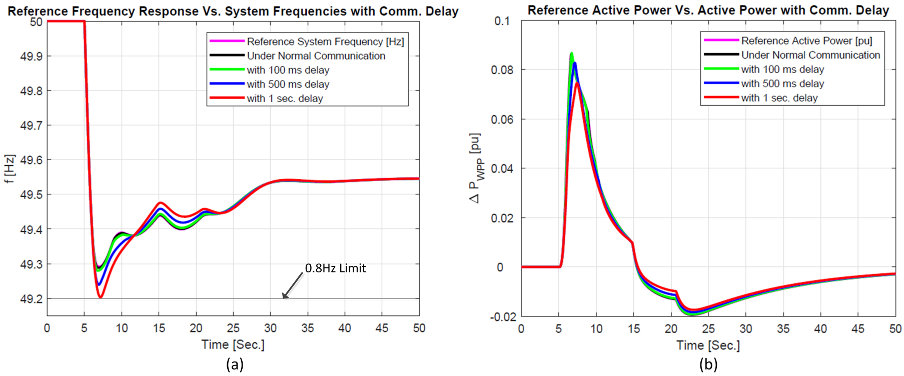


Fig. D.12: Figure showing at Partial Load **(a)** System Frequency Response and **(b)** Total Active Power under different delay conditions compared to the Reference Frequency Response and Reference Active Power, respectively.

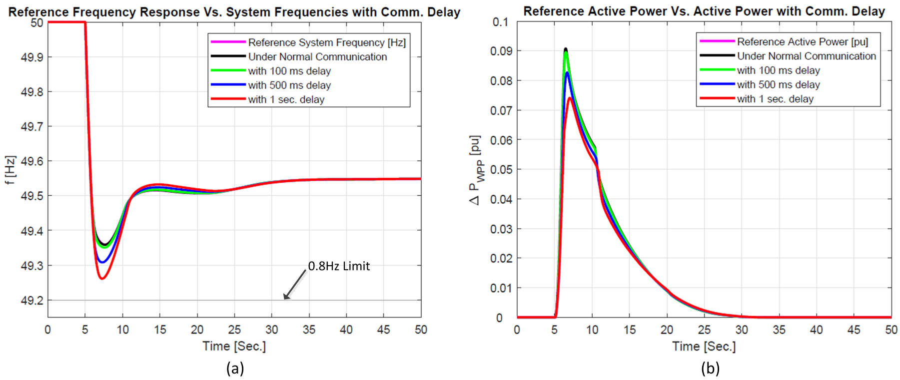


Fig. D.13: Figure showing at Full Load **(a)** System Frequency Response and **(b)** Total Active Power under different delay conditions compared to the Reference Frequency Response and Reference Active Power, respectively.

and ΔT_{Nadir} are given as:

$$\triangle f_{Nadir}[Hz] = f_{Nadir,Reference} - f_{Nadir,WithDelay} \quad \text{(D.2)}$$

And,

$$\triangle T_{Nadir}[Hz] = T_{Nadir,Reference} - T_{Nadir,WithDelay} \quad \text{(D.3)}$$

The comparison shown in Table D.8 is further presented graphically in Figure D.14.

The increasing values of Δf_{Nadir} in Figure D.14(a) also indicate that f_{Nadir} continuously decreases with the increase in communication delay for partial

Table D.8: Comparison of **(a)** f_{Nadir} and **(b)** T_{Nadir} obtained in *TestScenario*2 with that of Reference Frequency Response

		Test Scenario 2	
		Partial Load	Full Load
Reference f_{Nadir} [Hz]		**49.29**	**49.36**
Δf_{Nadir} **[Hz]**	Normal Comm.	0	0
	With 100ms delay	0.01	0.01
	With 500ms delay	0.05	0.05
	With 1 sec. delay	0.09	0.1
Reference T_{Nadir} [Sec.]		**6.95**	**7.5**
ΔT_{Nadir}**[Sec.]**	Normal Comm.	0.09	0
	With 100ms delay	0.14	0.06
	With 500ms delay	0.02	0.31
	With 1 sec. delay	-0.21	0.3

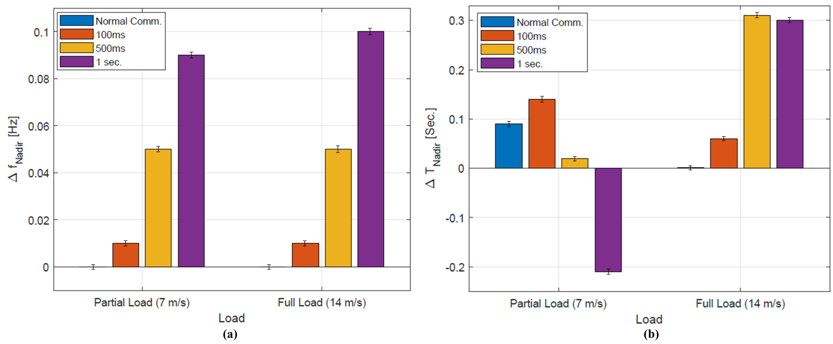


Fig. D.14: Comparison of **(a)** f_{Nadir} and **(b)** T_{Nadir} obtained in *TestScenario*2 with that of Reference Frequency Response at 95% Confidence Interval.

as well as full load. However, in Figure D.14(b), ΔT_{Nadir} for partial load is observed to be less than the reference T_{Nadir}, as indicated with the positive values. While, a negative value of T_{Nadir} is observed at a communication delay of 1 second, which indicates an increasing T_{Nadir} with increasing communication delays. It is also pertinent to mention here that $T_{SteadyState}$ remains the same for all cases, as clear from Figure D.12(a) and Figure D.13(a), therefore, not included in Figure D.14 for comparison.

D.6.3 Test Scenario 3

Test scenario 3 accounts for a private network connection for offshore WPP, while public network connections for the other two onshore WPPs and evaluated under partial as well as full load (see Table D.9). Figure D.15(a) and Figure D.16(a) show different system frequency responses at partial and full load, respectively, after inserting the communication link between the aggregator and a large share from WPPs (i.e. two-third of the total wind power production). The system frequencies obtained with different network delays are compared with the reference system frequency in section D.5.3. While, Figure D.15(b) and Figure D.16(b) show the total active power of the system at partial and full load, respectively, with different network delays compared with the reference active power in section D.5.3.

Table D.9: Test Scenario with Public Network Connections for both Onshore WPPs

	Wind Power Plants		
	Offshore	Onshore (Medium)	Onshore (Small)
Network Connection	Private	Public	Public
Wind Speeds	7 14	7 14	7 14

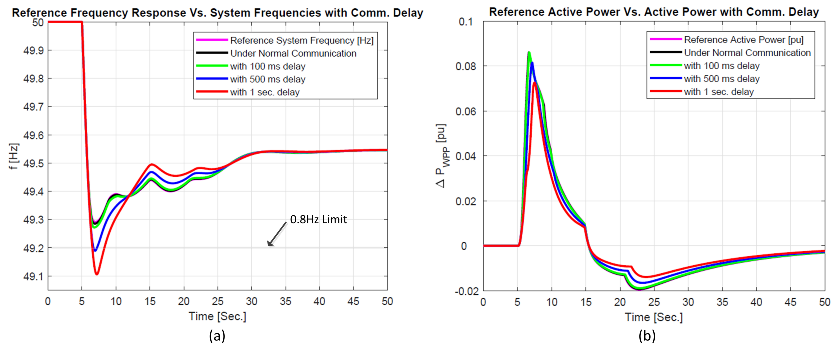


Fig. D.15: Figure showing at Partial Load **(a)** System Frequency Response and **(b)** Total Active Power under different delay conditions compared to the Reference Frequency Response and Reference Active Power, respectively.

According to Figure D.15(a) and Figure D.16(a), the affect on f_{Nadir} with an increasing communication delays become even more intense when a large share of WPPs is connected to the public networks. In case of partial load (Figure D.15(a)), the frequency limit of 0.8 Hz has even reached for delays of around 500ms. While in case of full load (Figure D.16(a)), the load shedding limit reaches for delays up to 1$second$ in the current setup.

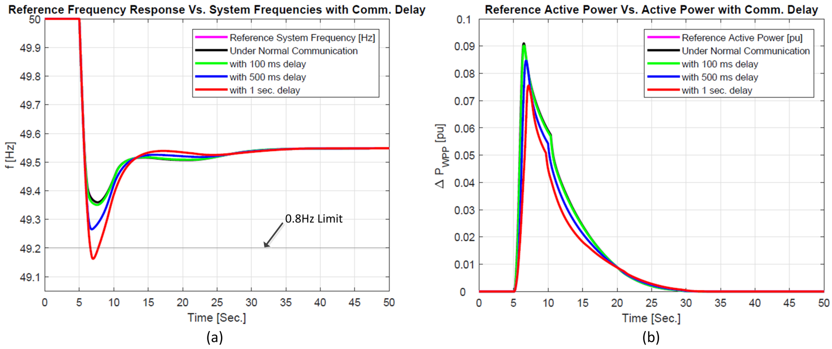


Fig. D.16: Figure showing at Full Load **(a)** System Frequency Response and **(b)** Total Active Power under different delay conditions compared to the Reference Frequency Response and Reference Active Power, respectively.

Results Discussion and Summary

Table D.10 provides, for partial load and full load, a comparison of each f_{Nadir} and T_{Nadir} obtained in *TestScenario*3 with the ones obtained from reference frequency response in Section D.5.3 in terms of Δf_{Nadir} and ΔT_{Nadir}, respectively. The comparison shown in Table D.10 is further presented graphically in Figure D.17.

Table D.10: Comparison of **(a)** f_{Nadir} and **(b)** T_{Nadir} obtained in *TestScenario*3 with that of Reference Frequency Response

		Test Scenario 3	
		Partial Load	Full Load
Reference f_{Nadir} [Hz]		**49.29**	**49.36**
Δf_{Nadir} [Hz]	Normal Comm.	0	0
	With 100ms delay	0.02	0.01
	With 500ms delay	0.1	0.09
	With 1 sec. delay	0.18	0.2
Reference T_{Nadir} [Sec.]		**6.95**	**7.5**
ΔT_{Nadir} [Sec.]	Normal Comm.	0.08	0
	With 100ms delay	0.19	0.05
	With 500ms delay	0.02	0.78
	With 1 sec. delay	-0.24	0.55

As in *Test Scenario 2*, the increasing values of Δf_{Nadir} in Figure D.17(a) also indicate that f_{Nadir} continuously decreases with the increase in communication delay for partial as well as full load. While, in Figure D.17(b), the same trend (as *Test Scenario 2*) for T_{Nadir} in case of partial loads can be observed in

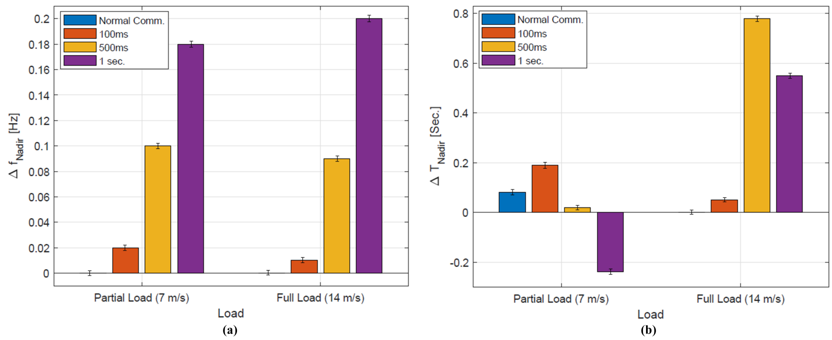


Fig. D.17: Comparison of **(a)** f_{Nadir} and **(b)** T_{Nadir} obtained in $TestScenario3$ with that of Reference Frequency Response at 95% Confidence Interval.

this scenario. In order to confirm this trend, the authors have plotted Δf_{Nadir} and ΔT_{Nadir} for a series of varying delays, provided in **Appendix D.8**. Furthermore, *Test Scenario 3* reveals that having a large share of ReGen plants on public communication networks may make the power system more prone to degrading the overall optimum frequency response in case the delays are increased from certain limit indicated in the test results. f_{Nadir} for partial and full loads is observed to be decreasing with increasing delays and the load shedding limit of $49.2Hz$ is even exceeded for (absolute maximum) delays of $1second$. However, as in *Test Scenario 2*, $T_{SteadyState}$ remains the same for all cases in *Test Scenario 3*, (see Figure D.15(a) and Figure D.16(a)), therefore not included in the Figure D.17 for comparison.

D.7 Conclusion and Recommendations

This paper assesses the impact of ICT on the frequency control support (FFR) from ReGen plants, with special focus on WPPs. Considerations on main characteristics of delays in public and private networks are shown using real measurements. Various delays according to statistical measurements on traffic are also considered. A coordination scheme for FFR including parameters as proposed in [12] is considered for analysis. Two operating conditions of wind power plants are taken into consideration namely partial and full load respectively.

The study reveals that in normal circumstances, private as well as public cellular based networks can support the provision of primary frequency control from WPP. However, in case of a disturbance, communication delays have a large impact on the overall response of ReGen plants on system frequency response as frequency nadir and time to reach it decrease with increasing network delays. Therefore, communication delays and their mechanisms must be considered in the design process of the proposed coordinated frequency control in [12]. Further, it has been ascertained that public networks are more prone to affect the overall frequency response due to stochastic nature of the delays compared to private ones where the delays are fixed and have low values. Based on the findings of this study, it is recommended that the design and tuning methodology for frequency control must account for the communication properties, such as delays in ICT especially when using public networks. Similarly, coordination and activation of ReGen plants for provision of frequency control must account for the ICT delays.

Additional work is required in order to get more insight on the impact of ICT on fast frequency response, such as: **(a)** account for a realistic power system model that takes into account transmission lines and ReGen plants location and thus a realistic mapping of ICT layer, **(b)** consider other control schemes and coordination methods in-line with the new ENTSO-E recommendations given in [24]. The current preliminary studies were done without employing control Hardware-In-the-Loop (HIL) framework where dedicated network emulators are used to capture performance and characteristics of a selected communication network technology. However, as a natural future step of the present investigation, these aspects will be addressed by implementing the described scenario in a dedicated HIL framework with the validation of two ancillary services from ReGen i.e. frequency restoration reserve (FRR, also known as secondary control) using a detailed model of the power grid e.g. modified 12-bus systems, and frequency containment reserve (FCR, also known as primary control).

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Appendix

D.8 A

Figure D.18 and Figure D.19 show a trend in **(a)** f_{Nadir} and **(b)** T_{Nadir} in comparison with that of reference frequency response under a sequence of increasing end-to-end network delay for *Test Scenario 2* and *Test Scenario 3*, respectively. It is worth to note that a positive Delta (Δ) value means "smaller than the reference value", while a negative value indicates "larger than the reference value".

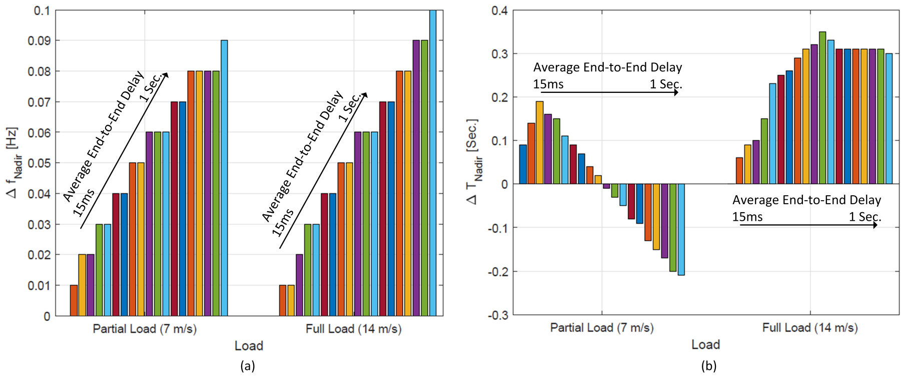

Fig. D.18: For Test Scenario 2, figure showing a trend in **(a)** f_{Nadir} and **(b)** T_{Nadir} in comparison with that of reference frequency response under a sequence of increasing end-to-end network delay.

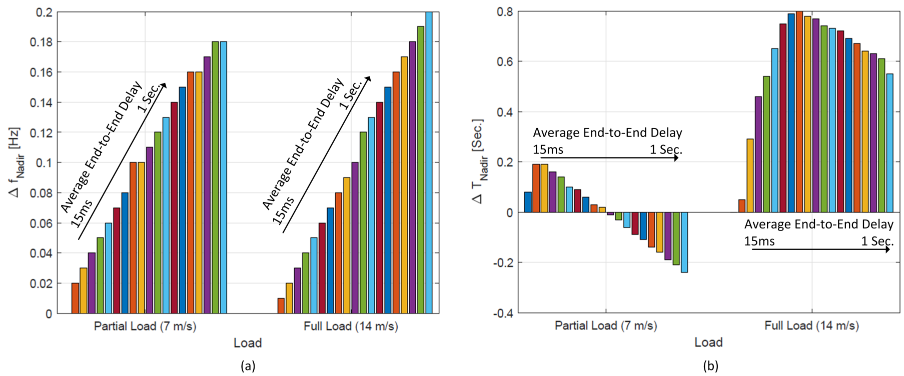

Fig. D.19: For Test Scenario 3, figure showing a trend in **(a)** f_{Nadir} and **(b)** T_{Nadir} in comparison with that of reference frequency response under a sequence of increasing end-to-end network delay.

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Paper E

Impact of Transport Layer Protocols on Reliable Information Access in Smart Grids

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Abstract

Time is critical for certain types of dynamic information (e.g. frequency control) in a smart grid scenario. The usefulness of such information depends upon the arrival within a specific frame of time, which in other case may not serve the purpose and effect controller's performance. In this context, transport layer offers different levels of end-to-end communication services to the applications. For instance, TCP guarantees the transport of messages between two ends, however, at the cost of high end-to-end delays due to the retransmission mechanism. Whereas UDP offers minimum end-to-end delays at the cost of unreliable, best-effort data transportation service. The research question raised in this paper is thus, which is preferred for the delay-critical applications of smart grids, and to what degree of packet losses and round trip times, TCP is preferable to UDP and vice versa. The question is addressed by analyzing the performance of UDP and TCP over imperfect network conditions to show how the selection of transport layer protocol can dramatically affect controller's performance. This analysis is based on a quality metric called mismatch probability that considers occurrence of events at grid assets as well as the information update strategy in one single metric which otherwise is not very intuitive and difficult to allow a similar useful comparison. Further, the analysis is concluded by providing a clear guide on the selection of the transport protocol to meet application requirements.

E.1 Introduction

Today, the governments of several countries are envisioned not only to upgrade the entire power grid system to smart grid but also to convert conventional fossil power plants into an entire renewable energy integrated system [1]. This goal will be attained by an active and reliable communication between various actors within the grid and a large scale installation of wind power and photo-voltaic (WP/PV) plants having a resilient communication infrastructure to coordinate their grid support services. This will bring new operational challenges for the system operators and will significantly change the control and operation of the existing distribution grids. For instance, with the high foreseen penetration of Renewable Generation (ReGen) plants, the electrical grid could face frequency and voltage problems [2]. In order to enable high penetration of ReGen plants in future and utilize them in a coordinated manner, the Distribution System Operator (DSO) would need to deploy private and/or use public communication networks.

Implementing new large-scale communication infrastructure is not economically feasible; therefore, existing communication infrastructure should be considered and further investigated for improved performance. Nowadays, cellular networks (EDGE, LTE etc.), fiber optics, cable internet and xDSL are already widely deployed by the telecom operators and have high geographical coverage [3], which could be used to connect the ReGen plants to the system operators. However, shared network solutions may not be able to provide quality-of-service required by the grid services and could bring additional risk, especially if they are exposed to internet access. Data exchange may suffer from stochastic non-controllable delays and packet drops. Therefore, a high consideration is required while designing systems like power grids that provide high dependability [3].

In smart grids, a system operator being in-charge of controlling multiple ReGen plants will depend exclusively on the information provided by these plants for sending correct set-points. It will, therefore, become very critical for the system operators to be well aware of the status of the connected plants. Especially, in case of delay-critical applications (e.g. protection and control related) where a delay of few milli-seconds can cause the information to become outdated for the control center, which ultimately can become a big risk for the entire power system. In the worst-case, this may result in an unstable power grid and/or a blackout.

In order to ensure such control and monitoring, the International Electrotechnical Commission (IEC) has developed protocol standards for electric power systems and substations. For instance, IEC-61850 identifies the general as well as specific functional requirements for communications in a substation [4]. These requirements aid in the identification of the desirable services, data models, application protocol as well as all the underlying layers in the communication stack defined by the OSI reference model that will meet the overall requirements. However in the OSI model, it is the transport layer that is responsible for providing different levels of end-to-end data transportation service quality to the applications [5]. For instance, TCP provides a connection oriented [6] service that includes a mechanism to acknowledge the reception of data and a retransmission in case of lost data/ acknowledgment. This allows a guaranteed transmission/reception of data packets in a causal order. TCP also provides congestion control, flow control and reliability by adding headers with the original message. However, due to the retransmissions and congestion control mechanisms, TCP generally suffers with relatively higher delays in case of dropped packets or time-outs. UDP, on the other hand, provides connectionless, best effort service [7] with no guarantee of message delivery. It does not provide services like congestion control, flow control and reliability, therefore, faster than TCP. Due to the lack of such functionality in UDP, the application must accept that packets may very well be lost in the network or arrive in different order than it was sent from the source. Typically, in practice TCP is used in industrial protocols such as MODBUS/TCP and IEC-61850 for communicating over networks [8] [9]. Therefore, the research question raised in this paper is thus, which is preferred and to what degree of packet losses and round trip times, TCP is preferable to UDP and vice versa for various time critical applications in smart grids. The trade-off between using TCP and UDP, is in fact a trade-off between losing data in the network or accepting much higher delays in data reception.

E.1.1 State-of-the-Art

The performance analysis of transport layer protocols over communication networks in general has been addressed in several papers. For instance, [10] analyzes the performance of TCP, UDP and some improved protocols based on TCP in adhoc wireless networks based on throughput, packet loss, jitter, end-to-end delay and fairness. Reference [11] presents the same performance evaluation as [10] but on wired network environment. In [12], an analysis of both the transport layer protocols in a wireless LAN 802.11 test bed with different scenarios has been provided considering the flow fairness with a single access point and varying the number of mobile stations. These papers lack to address the performance of transport layer protocols in relation to the smart grid applications especially focusing the standards on the communication and control of electric power systems as, for instance, proposed by IEC. However, in [13] we analyzed information reliability over various imperfect communication network conditions with IEC-61850 MMS using the concept of mismatch probability. A resulting trade-off between quality of controller performance and mismatch probability has also been identified in [13]. Still, there's no solution proposed to decrease the probability of information mismatch and improve quality of the controller performance in [13]. Therefore, this paper is extending the previous analysis by providing a clear guideline to optimize communication performance in IEC standards (e.g. IEC 61850, IEC 60870) that currently use TCP as a transport layer protocol [8, 9].

In this paper, we analyze the trade-off between end-to-end delays and packet losses for the two transport layer protocols. This analysis is based on the information accuracy in the communication between plant controllers and the control center. It is hypothesized that a correct and timely reception of information leads to good/expected controller performance, while delayed information may cause information mismatch between the two ends, causing degraded controller performance. The information accuracy in a given scenario is measured using an information quality metric known as mismatch probability (mmPr). mmPr was first defined in 2010 in [14] and since then it has been applied to different scenarios, e.g. in [3, 15, 16] to improve smart grid control. The benefit of using mmPr as a quality metric is that it considers both the occurrence of events and the update strategy in one single metric and put those in relation to the dynamics of the grid scenario [16]. This otherwise is not very intuitive and difficult to allow a similar useful analysis. Secondly, it has been ascertained in [17] that the simulation results on mmPr and voltage quality under the considered controller show same qualitative behavior. This implies that the mmPr as a quality metric can be used to identify relevant delay ranges as well as the update period interval ranges that are expected to impact voltage quality performance. [17] also concludes that mmPr can be used to optimize communication network and information access configurations without the controller realization. Therefore, this paper only focuses on the network aspects of the communication without the realization of a specific controller. Finally, based on the outcome of the analysis, a solution is proposed that serves as a guide for the right selection of transport layer protocol, specifically in IEC 61850/60870 for various time critical applications in smart grids. The main contributions of the paper are:

- A procedure for estimating the information accuracy over congested communication networks.
- Based on the rate of occurrence of events, define a reference graph to serve as a guide to select appropriate transport layer protocol for a specific application.

The remainder of this paper is organized as follows: Section E.2 defines and explain the quality metric selected to compare performance of the two transport layer protocols. Section E.3 describes the case specific scenario adopted to get simulation results. Section E.4 provides evaluation of simulation and analytical results and finally Section E.5 summarizes the conclusion drawn and directions for future work.

E.2 Information Quality Metric

As described in section E.1, for delay-critical applications in a smart grid system, the reception of correct status information within a predefined frame of time is crucial for the control-center to take correct actions. The added delays due to, for example, poor network conditions can cause the information to become outdated for the control center. This is because the information age generally increases (approximately linear in case of periodic updates) as a function of the delay [17]. This implies that in order to process, for instance, 1 million information elements, each element should have the same priority to get through, which means to create a huge amount of high priority traffic − not good for the end-to-end delay. Secondly, since all information elements are potentially very different from each other, it is difficult to see the area where each element is sensitive to the delay − thereby giving a reason to priorities the data. Hence, both of these reasons contribute to a potentially erroneous prioritization of data packets in a network. Eventually, this necessitates to have a quality metric that can measure the amount of information correctness (based on the information dynamics) and allows to see if it is worth to spend too much of resources to improve quality of the controller performance. Therefore, in order to evaluate the extent of information correctness, we make use of mmPr as a quality metric, defined in the following.

E.2.1 Defining Mismatch Probability (mmPr)

In order to model mmPr for a specific case in in this paper, communication between a controller at some ReGen plant and a control-center is considered, which are located at different geographical and network locations. The control-center at certain control period accesses the dynamically changing controller's status information. This information access occurs over a shared network and thus offers stochastic end-to-end delays. Here, mmPr is defined as:

$$mmPr = Pr(I_{cc}(t_c) \neq I_{ct}(t_c)) \tag{E.1}$$

Here, I_{CC} and I_{CT} are the information available at control-center and the controller respectively, while t_C is the control time where the two sets of information are compared. This paper uses the proactive periodic access scheme for the controller to send its status updates [14]. In the periodic access, controller sends the state of the information (current status) to the control-center after every specified time interval (update rate), as shown in message sequence diagram in Figure E.1. This update rate is important as it can be used to determine the entire generated traffic. Notation used for the message sequence diagrams in Figure E.1 is as follows: D_i denotes the time at which i^{th} message is sent to the controller, while d_i is the delay experienced by this message. R_i is the time at which control-center (requester) needs the status information from the controller. E_i is the event detected at any time interval by the controller. The update process is assumed jointly independent to the event, delay, and request processes [14].

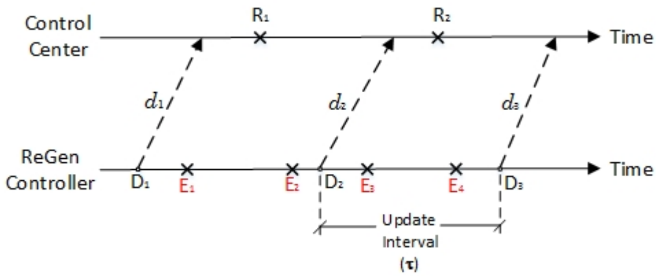

Fig. E.1: Message sequence diagram showing proactive, periodic update of information with a mismatch case scenario

The case of information mismatch in TCP and UDP can be observed in Figure E.2(a) and E.2(b), respectively. For TCP, in Figure E.2(a), it has been assumed that the communication connection is already established, i.e. there is no three-way handshake involved. In Figure E.2(a), R_1 results in a mismatch from E_1 because the time when control-center receives information, the status on ReGen controller had already changed through an event E_1. Similarly, during message transmission, when a message is dropped due to, for instance, congestion in the network, it is retransmitted after a transmission timeout period. In case the congestion in network is too high and the message is dropped many times, it will be sent several times depending on the retransmission algorithm used. Although this mechanism ensures/guarantees transmission of message at the control-center but at the cost of increased end-to-end delay which may become a cause of a mismatch of information between the two electric devices. This can be observed in Figure E.2(a) for information update between events E_3 and E_4. The suspected impact would be a wrong decision that leads to a wrong controller action. However, R_3 in Figure E.2(a) succeeds in receiving correct information as no other event occurred during this period. In case of UDP, Figure E.2(b), a loss of information is not compensated with a retransmission. This may also become a cause of information mismatch depending on the events occurring in the controller side, as shown in Figure E.2(b).

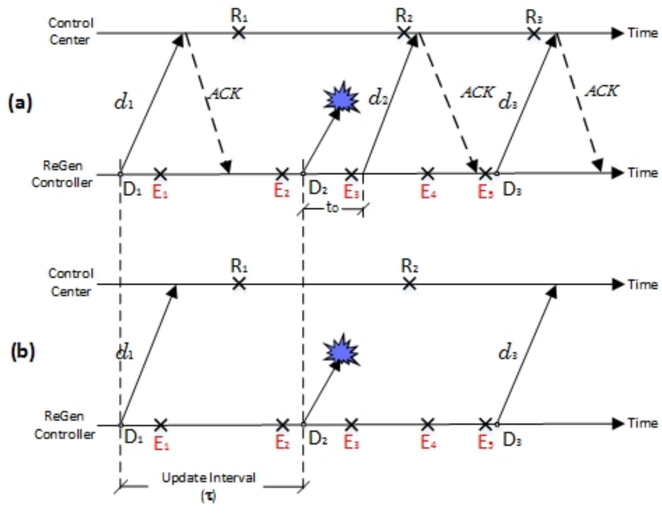

Fig. E.2: Message sequence diagram showing proactive, periodic update of information with an information mismatch case scenario for (a) TCP and (b) UDP

To support our analysis, we make use of existing mmPr models, presented in [14], considering raw packet losses (UDP) versus the prolonged delay caused by packet losses (TCP) in the given model. The model for mmPr used in this paper is given in (E.2): [for detailed description of this model, see [14]]

$$mmPr = \int_0^{\infty} exp(-\int_0^t \tau F_D(s)ds) A_E(dt) \tag{E.2}$$

Here, τ is the status update rate, F_D is the CDF of delay and A_E is the CDF of backward recurrence time for an event process that is a stationary renewal process [12]. Packet losses for UDP in this model can be regarded as a thinning of the update process, i.e. a reduction of the rate τ with the factor $(1 - P_{LOSS})$ such that $\tau_{eff} = \tau\ (1 - P_{LOSS})$. Whereas, packet losses for TCP lead to a higher delay and in particular delay CDF. From the model shown, it is neither clear nor intuitive as to which change has the most severe impact on mmPr, and this is what we assess in section E.4.

E.3 Evaluation Setup And Measurements

The assessment in this paper relies on measurements obtained from a network setup where, a control-center is connected to the ReGen plants, as shown in Figure E.1. The control-center and the controller within the ReGen plants are time-driven, where for each controller execution time $R_1(t_1)$, $R_2(t_2)$, ... , $R_N(t_N)$ the ReGen plants send updated flexibility values $D_1(t_1)$, $D_2(t_2)$, ... , $D_N(t_N)$. The controller execution times are equidistant $T_S = R_2(t_2) - R_1(t_1) = R_N(t_N) - R_{N-1}(t_{N-1})$, as well as the offset times $T_{offset} = R_1(t_1) - D_1(t_1)$ denoting the time gap between sending the updates at the ReGen plants and the control-center execution times. The control step is $T_S = 1$ second, which corresponds to second-level scale necessary for load frequency control [18]. The offset value is considered to be constant and equal to $T_{offset} = 0.5$ seconds [8].

Communication between ReGen and the control-center is established first via TCP and then with UDP connection. With both TCP and UDP sockets, end-to-end delays at multiple packet loss rates are captured. The mmPr, defined in Section E.2, is based on end-to-end delay measurements recorded from the time when ReGen plant sends a status update packet out to the time it is received at the control-center.

E.3.1 Simulation Setup

Analytical modeling of TCP throughput delay in [19] provides a mathematical model to compute delay for bulk TCP data. However, using the model in [19] and other such models for a small size of packets (in the order of few hundred bytes or less) and periodic interval of 10 seconds do not serve the purpose. This is because the sender congestion window for such settings does not exceed a certain limit. Normally, a packet would take half the duration of RTT to be received (at the receiver) if successful and would take duration of Timeout if packet is lost. Considering such settings, a network simulator can provide a mechanism to measure the delay that a packet of few bytes experiences to get across from sender to the receiver.

OMNeT++ is, therefore, used as a network simulator to obtain end-to-end delay traces. In order to obtain realistic traces of communication delays, a 3G network is realized offering gross data rate up to 200 kbps. The two communicating entities are placed for simplicity of setup at length of only 10 meter. Instead of attenuation and noise, we in this paper only focus on cross-traffic. By mimicking the information exchange shown in Figure E.1 and Figure E.2, end-to-end delay measurements have been collected from ReGen to the control-center.

The delay traces are obtained with different pairs of linearly distributed link propagation delays (D_L) and packet error rates (PER) for TCP as well as UDP, using identical network environment. For each pair of D_L and PER, a set of 100 messages, each of 100 bytes in length at an exponentially distributed period of 10 seconds, was sent from controller to control-center to capture end-to-end delay traces. A set of 100 messages has been considered, specifically, to take the CDF of the end-to-end delays instead of one single delay for each group of network parameters. In case of TCP, this set of 100 messages are sent under a single three-way handshake. This assumption is made because the purpose here is not to get the exact model of TCP, but to get the potential solution of the impact that the additional delays have on the mismatch probability.

The end-to-end delay traces were then used to determine mmPr by comparing the time of reception of information with the exponentially distributed random events generated at a specific mean interval. Based on the results of mmPr, a comparison has been made to see which of the two protocols provide better performance in terms of information accuracy at different propagation delays and packet loss probabilities. Figure E.3 shows the complete simulation layout.

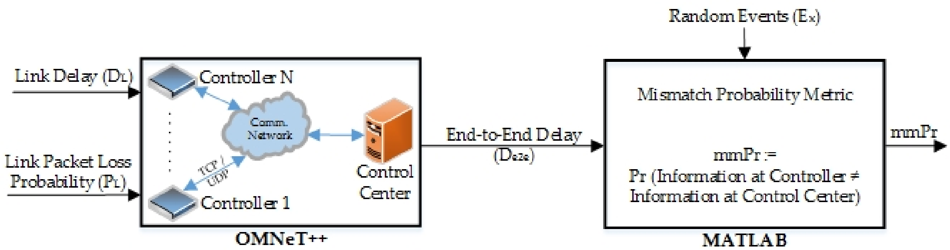

Fig. E.3: Simulation Layout.

E.4 Performance Study Of TCP Versus UDP

E.4.1 Analysis by Simulation

This section presents the results of simulations, showing the impact of TCP and UDP on mismatch probability at two different packet loss probabilities. The results obtained via delay traces are also compared with those obtained through the analytical model (shown in green). A trade-off between the packet losses and added delays to the information will be presented in the end that would help selecting a protocol for the time critical message types in smart grids.

We estimate the mismatch probability by comparing at time instances of information access with the actual value. The average of mismatches yields the mmPr estimate:

$$\widehat{mmPr} = \frac{1}{N}\sum_{i=0}^{N} I(I_{cc}(t_c) \neq I_{ct}(t_c)) \tag{E.3}$$

Figure E.4 shows the impact of increasing propagation delay on mismatch probability (mmPr) considering perfect conditions for the network with no loss of information (i.e. PER = 0). It can be observed that under this condition TCP and UDP show the same performance approximately around 2.5 seconds of the propagation delay. However, as the delay continues to increase, the mmPr for TCP increases abruptly as compared to UDP. As the network is loss-less, this difference is because of the transmission timeout of TCP. Analytical results for UDP's mmPr in Figure E.4 clearly indicate that for low propagation delays it gives the same results as obtained from the simulation model, but then deviates a little. This deviation isbecause the simulation results are gained from a combination of delay traces, and we expect the delay distribution to be slightly different from exponential distribution. This, nevertheless, matches the conclusions drawn in [14] i.e. more deterministic the distribution, higher the mismatch probability.

The difference of mmPr between TCP and UDP becomes more prominent as more and more packets are dropped i.e. higher PER. This is shown in Figure E.5 where the rate of packet loss in the network is increased to 10%. In case of TCP, each time a packet is lost, it is retransmitted causing delay in the information packet. The retransmitted information packet from the controller may become outdated for the control-center, causing mismatch of controller state information. The huge variation in the results is due to the variation in the mean end-to-end delays that depends upon the time a packet is lost during transmission as well as the cross traffic involved. However, in case of UDP, packet losses have no significant impact on mmPr. If any information packet is lost during transmission, the next request message can recompense

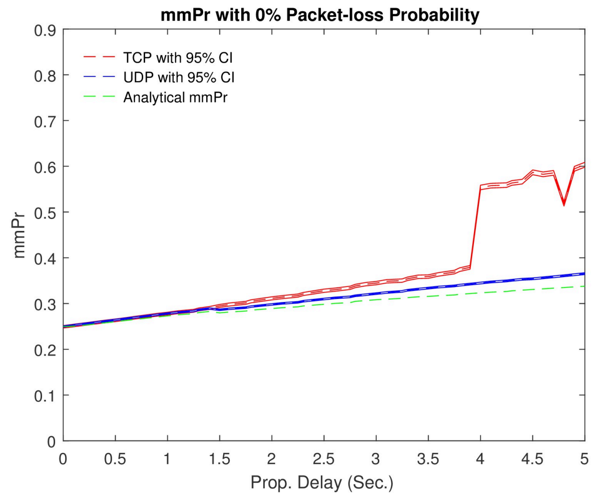

Fig. E.4: Mismatch probability versus propagation delay with 95% confidence interval (CI) at PER of 0%

the job of getting latest information, as observed in Figure E.5. It is also important to note that percentage of packet losses is higher for TCP than UDP simply because, TCP has more number of packets for request/responses due to the acknowledgment mechanism. It can, therefore, be concluded that higher packet loss probabilities cause TCP performance to degrade faster than UDP.

E.4.2 Trade-off between packet loss (P_{LOSS}) and delay

Considering a simple case with delay and event, inter arrival processes are exponentially distributed with rates λ (event) and v (delay), the following expression of the mismatch probability has been derived from (E.3) (for detailed derivations see [14]):

$$mmPr = \phi e^{\psi} \frac{\Gamma(\phi + \psi)}{\psi^{\phi+\psi}} F_{\Gamma(\phi+\psi,\psi)}(1) \tag{E.4}$$

With $\phi = \lambda/v$, $\psi = \tau_{eff}/v$ and $F_{\Gamma(a,b)}$ the CDF of a gamma distribution with parameters a and b. Here, the value of deterministic delay is given by $D \equiv 1/v$, while τ_{eff} is given by $\tau \times P_{LOSS}$.

The important aspect to notice here is that the mmPr in reality is a complex function of ratios between the update rate, event rate and the delay rate, respectively. We, therefore, use this model to elaborate the trade-off between delay and packet losses reducing the effective update rate. This later is mapped into a comparison between UDP and TCP performance, since as

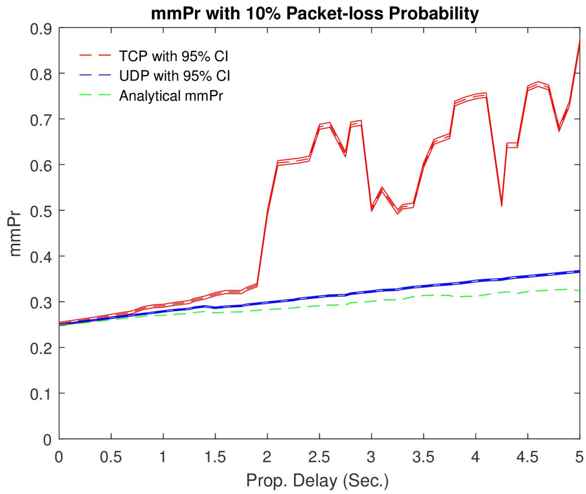

Fig. E.5: Mismatch probability versus propagation delay with 95% confidence interval (CI) at PER of 10%

(E.3) shows, the distribution of the delays (and events) are also important and for TCP these are certainly not exponentially distributed as we assume in the simple analysis.

The results shown in Figure E.6 illustrate the trade-off between packet loss probability and the delay it takes to achieve same level of mismatch probability. The point we make here is that for a given P_{LOSS} probability, UDP leads to an effective reduction of update rate, which ultimately reduces the mmPr. If for the same P_{LOSS} we use TCP (where the packet loss is reduced to zero through retransmissions), the plots in Figure E.6 show the mean delay that TCP should attain if the same mmPr should be achieved. Therefore, if a reliable protocol (e.g. TCP) can do this faster, then this protocol outperforms the UDP, and if it is slower, then UDP performs best.

Comparing these to the results with Figure E.4 and Figure E.5, it seems that in general the TCP is above the timely threshold shown in Figure E.6, indicating that the TCP assessed is in general performing poorly in the situation of sending dynamic data over network. However, as the plots in Figure E.6 also indicate, there is room for adjusting e.g. timeout values to accommodate for the losses for slow dynamic information (lambda = 0.1 events/sec), where a significant amount of time can be spent on retransmission before it no longer pays off. For faster information dynamics (here, 1 event/sec in average) there is so little time in overhead that it is very unlikely to be possible. The TCP timeouts in relation to this trade-off will be focused in our future research. On the other hand, other protocols may also be designed, e.g. multiple transmission of same information via UDP which reduces packet losses to nearly zero at the cost of a potential added delay, as long as the complete message transfer delay (end-to-end) is kept below the shown graphs, or else a simple UDP based protocol suffices.

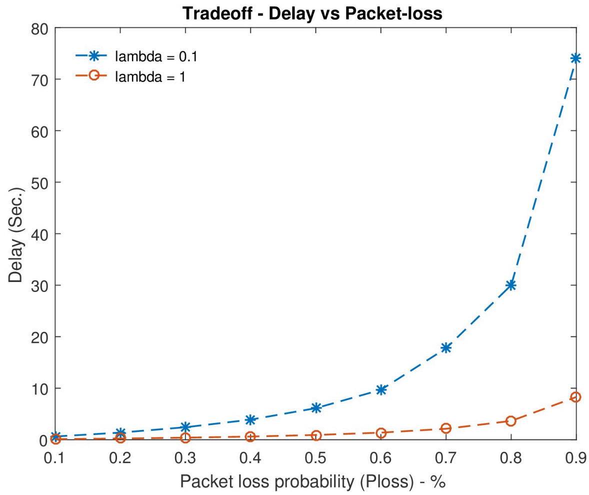

Fig. E.6: Trade-off between packet-loss and end-to-end delay for a given propagation delay at minimum and maximum event rates (lambda).

E.5 Conclusion

By using the concept of mmPr as a quality metric, this paper investigates how the selection of transport layer protocols effects the quality of information received and that the selection of UDP or TCP is basically a trade-off between loosing data in the network or accepting much higher delays in reception of data, respectively. It has also been shown that the trend in mmPr for UDP remains approximately the same for all cases of packet loss probabilities from which it can be concluded that UDP should be preferred for time critical message transmissions in smart grids compared to the standard TCP model assessed. However, the second aspect of this analysis shows that TCP is most suitable for information which changes slowly, and that there is room to adapt TCP e.g. by adjusting timeout values to achieve better performance. The analysis made in this paper, however, forms a basis to optimize the performance of IEC standards that defines requirements for communications in a substation.

The information access scheme used in this paper was proactive with periodic updates. This leads to the future direction of studies e.g. performance evaluation of transport layer protocols based on reactive (request-response based) and proactive access with event driven updates. Moreover, based on the verification of these simulation results in a Real-Time Hardware-in-the-Loop environment using IEC-61850, an adaptive algorithm will be developed by modifying the current communication protocols.

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Paper F

ICT Requirements and Challenges for Provision of Grid Services from Renewable Generation Plants.

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Abstract

The penetration of renewable energy into the electricity supply mix necessitates the traditional power grid to become more resilient, reliable and efficient. One way of ensuring this is to require renewable power plants to have similar regulating properties as conventional power plants and to coordinate their grid support services (GSS) as well. Among other requirements, the coordination of GSS will highly depend on the communication between renewable plants and system operators' control rooms, thereby imposing high responsibility on the under lying communication infrastructure. Despite such a widespread deployment, it is still neither completely known which communication technology solutions are currently in use, nor it is clear which of these technologies best fit to access and control these renewable plants in future. This is because of varying communication requirements for different GSS applications – in terms of data payloads, sampling rates, latency and reliability. Therefore, this paper presents a brief survey on the control and communication architectures for controlling renewable power plants in the future power grid, including the communication network technologies, requirements, and research challenges. To help identifying research problems in the continued studies, this paper attempts to ascertain how the underlying protocols in a communication stack influence timely and reliable communication in the said scenario.

F.1 Introduction

This The use of renewable generation (ReGen) plants such as solar PVs and wind power has increased drastically over the last couple of years, playing a significant role in climate change mitigation as well as several economic benefits [22]. According to the REN21's 2017 report [43], in 2016 renewable power capacity has set new records of adding 161 gigawatts; increasing the global total by almost 9% compared to 2015. Here, energy production from solar PV accounts for around 47% while wind power to be 34% of the total addition. The investment in increasing the capacity of renewable power (including hydropower) has approximately doubled compared to the investment in fossil fuel based power generation, reaching USD 249.8 Billion [43]. Countries like USA and China are heavily investing in wind, solar, hydro and biofuels [43]. At national level, around 30 countries at present have renewable energy contributing over 20 percent of the total energy supply. Where Norway and Iceland are on the top of the list to generate maximum of their electricity using renewable energy, but rely predominantly on hydro-power and geothermal energy, respectively. Other countries, such as Denmark, have set goals to reach 100% renewable energy in the future.

The Danish grid has evolved in the last decades from a classical top-down hierarchical structure dominated by large power plants to a power grid with high penetration of renewables and dispersed generation (see Figure F.1). Currently small wind turbines and solar PV systems are connected in the low voltage distribution grids, medium size PV systems and wind turbines are spread over the distribution grid while the large off-shore wind power plants are tight to transmission system. Nowadays, the circulation of power in distribution grids as well as reverse power flow to transmission system is a challenge for classical operation and control schemes since more renewable generation is expected in the near future. The government in Denmark aims to switch the total energy supply to 100% renewable energy by 2050 [14], which will be accomplished by a large-scale integration of wind power (WP) and solar photovoltaic (PV) plants. As a mid-term goal, the Danish government targets to achieve a power production of at least 50% from these power sources by the end of 2020. For this, the WP generation capacity of 4792 MW (which is 33.2% of total electricity consumption [1]), will be increased to 6700 MW in 2020 [38]. While, according to [12], the PV generation capacity of 553 MW to-date, will be increased to 1000 MW in 2020.

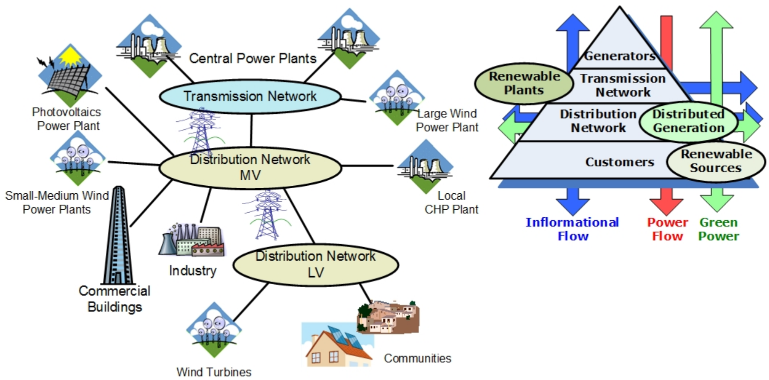

Fig. F.1: Current structure of the Danish power system.

The foreseen high penetration of WP and PV into the electricity supply all over the world imposes the requirement that the bulk addition of large scale renewable generations to the grid to not be detrimental to the overall stability of the power system. One way of ensuring this, is to require WP and PV plants to play a role not only into the energy production, as it is today, but also into the delivery of system services which are needed to ensure the system stability comprising both transmission and distribution level, namely ancillary services. This fact leads to fundamental changes in the way transmission and distribution system operator (TSO and DSO) will have to use GSS from ReGen plants to manage the voltage and frequency stability in the future power system, which will continuously evolve through new interconnections and use large scale renewable technologies. According to [21], the amount of power system needs for ancillary services in the future will increase with high share of ReGen. The flexibility in the TSO/DSO interaction will also be more and more important, as well as the growing role of DSOs in the ongoing process to accommodate concentrated large scale renewable energy generation in the distribution grids. The technology analysis of WP and PV over the last few years has also confirmed their technical and operational capabilities to provide GSS like frequency and voltage support [21].

Nevertheless, knowledge gaps and need for further research are also identified in the area of providing ancillary services from ReGen. For example, according to [21], in the context of ancillary services delivery from WP/PV plants, further investigations strengthening system reliability regarding the following is necessary: **a)** Faster and reliable communication (between WP plants and control center), **b)** Dedicated tuning of the control strategies, **c)** Control within the plants, **d)** Estimation of available power as well as coordination of offshore/onshore WP plants in providing reactive power and voltage control at their onshore point of coupling, etc.

On the other hand, the literature review [8, 10, 18–21, 28, 35–37, 40] also reveals the fact that at the present development stage of WP and PV units with respect to delivery of ancillary services, most of the research has been conducted with focus only on a single technology, without any insight on the opportunity to coordinate system services from different ReGen technologies. Moreover, the impact of information and communication technologies (ICT) in the delivery of ancillary services has not been a point of focus. Communication both within the ReGen plants and between ReGen plants and control centers highly depends on the underlying communication and network infrastructure and failure of this component can lead to dire consequences [34]. Therefore, this paper not only presents a brief survey of the communication technologies, standards and protocols that can be a candidate in the provision of GSS from ReGen plants but also highlights some of the key research questions and challenges that need to addressed for a future resilient power system.

F.2 Communication And Control Architecture

Large-scale offshore wind power plants connected to the transmission system will be the main renewable generation driver in the future Danish power system [9]. While at the distribution level both onshore WP and large scale of PV plants will have to support the power system with regulating properties. Figure F.2 illustrates how large-scale ReGen plants will be accommodated without jeopardizing the stability and security of the future power system. A proper coordination strategy between ReGen plants also needs to be developed. As depicted in Figure F.2, the coordination between ReGen plants is anticipated to be included in a power plant controller at each power system level, namely distribution and transmission, respectively. At the transmission and distribution system level, ReGen controllers will be used to control and coordinate the ancillary services provision from large-scale offshore WP plants and onshore WP plants as well as PV plants.

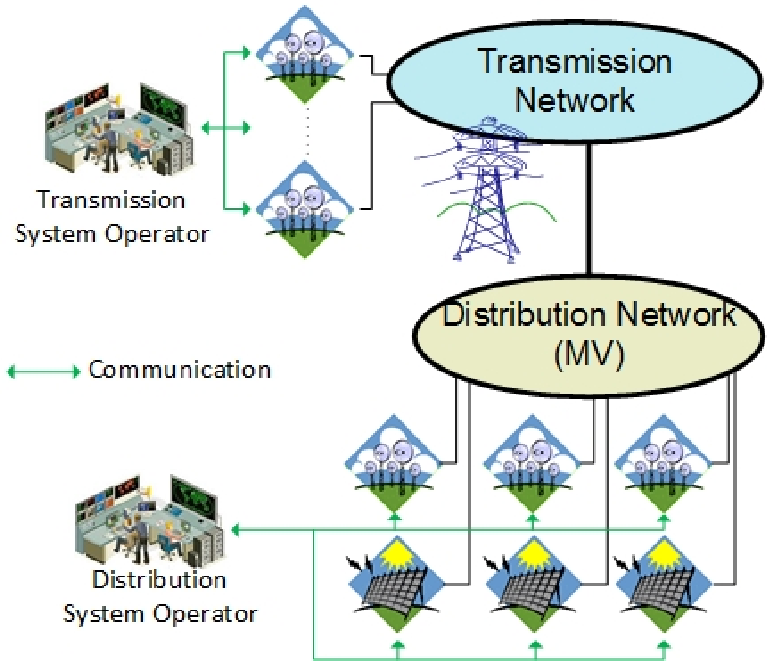

Fig. F.2: Resilient power system with coordinated control of the ancillary services from ReGen plants.

The underlying communication infrastructure in such a scenario must support the provision of required ancillary service functionalities and meet the performance requirements. This infrastructure will not only be responsible to connect large number of ReGen plants to the control center, but will also manage the complicated device communications. Therefore, according to [17, 41], it will be constructed in a hierarchical architecture with interconnected individual subnetworks, where each subnetwork will take responsibility of separate geographical regions.

F.2.1 Control Architecture

The control of renewable power plants in the future smart power system can be categorized into two control architectures, namely hierarchical centralized control and decentralized control respectively.

Centralized Control Architecture

The centralized control concept, depicted in Figure F.3, is based on the current setup used by system operators. Depending on the power system status, the control center activates certain control functions on the Aggregated Control level acting as the central controller. Optimal dispatch functionality and wind/PV forecast, accounting for the availability of the assets to provide a given GSS are included in the aggregated control, as well as the measurements with the status of WPPs and PVs units. The set-points to the WPPs and PVPs are sent by the central controller according to the control and dispatch algorithm. Notice that there might be several central controllers acting in different locations depending on the number of energy aggregators present in the market [30].

Decentralized Control Architecture

Contrary to the centralized control structure, in the decentralized control concept, there is no communication between plant controllers and upper hierarchical control level (see Figure F.3). Each plant control can communicate with the other parallel local plant controllers with predefined characteristics depending on the control phenomena. In order to provide better control performance for a given GSS, data exchange between the plants may be necessary. An optional solution can also be that plants in the transmission system communicate with plants in the distribution system to provide better performance regarding, for instance, frequency control stability support [30].

The forecast methods in the decentralized control concept can be used for each plant individually to provide a given GSS, when feasible. However, optimal dispatch is not feasible for this control concept due to the lack of a centralized control element [30].

F.2.2 Required communication properties and supporting network technologies

A resilient communication network is required for most cases to coordinate and ensure that measurements and set points are correctly exchanged between entities in the system. Several properties of communication are highly relevant, which at the end boil down to the amount of investment required in order to support the envisioned grid control services. Few most important communication properties are listed below [29]:

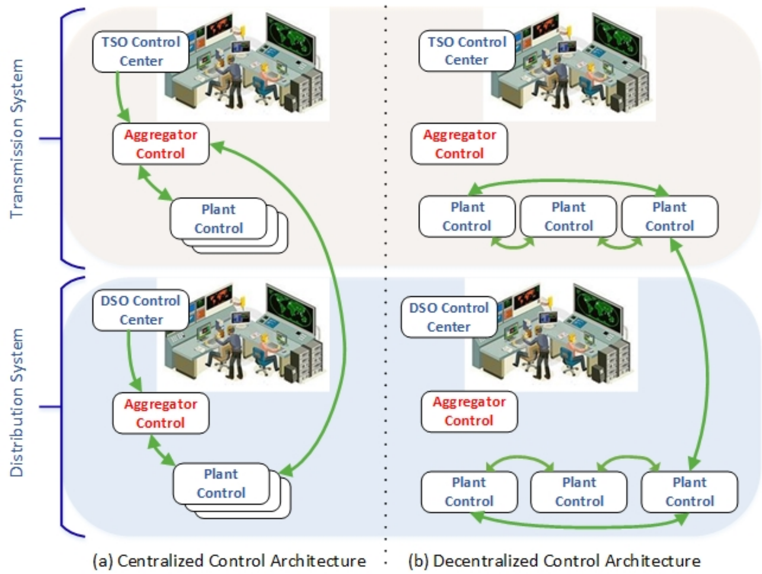

Fig. F.3: Centralized Vs. Decentralized Control Architecture

1. **End-to-end delay:** Time taken by a message to go from source to destination across the entire network.

2. **Packet loss probability [%].**

3. **Range:** The range of network has implications on what type of performance metrics can be achieved.

4. **Security:** A note on how sensitive the data being exchanged is for being exposed to malicious attacks. The most desirable properties of a secure network communication include confidentiality, authentication, message integrity and non-repudiation. Security is, in some cases, rationale enough to do the investment in private fiber connections, which then also affects other parameters of communication.

5. **Scale:** The number of sources that need to interact is critical as it affects the overall data communication patterns, and thereby, traffic patterns metric.

6. **Communication channel capacity:** It is the highest rate of information that can be transmitted through a channel. While designing a communication link between two entities it is important to model a channel and estimate the amount of information that it can pass through, keeping in mind the effects of channel attenuation, noise induced as well as the non-linear effects.

In addition to the above mentioned communication properties, there are certain other properties to be considered while developing a communication link between two plant controllers. For instance, message size, buffer size in messages, channel bit error rate, congestion loss, corruption loss, packet error rate etc. These are typically metrics related to specific layers in the OSI model, but the goal in this paper is to map all these metrics into the first two metrics: end-to-end delay as a stochastic variable and packet loss probability (see Section F.4).

Based on the above mentioned communication properties, several network technologies can be used to support communication between ReGen plants as well as the communication between ReGen plants and control center. However, a single technology does not suit all the applications. There is always a best fit of a technology that may be selected for a group of GSSs from ReGen, which are either operating in the same domain or have similar communication requirements. Therefore, before selecting a communication technology for a particular GSS, it is necessary to have a thorough analysis so that the application requirements are matched directly with the properties of a technology. The available network technologies can be categorized into wired and wireless communication technologies.

For communication between a large number of ReGen plants and the system operators (DSO/TSO), data (in terms of status updates, set-points) will be exchanged at much higher rate (depending on the GSS) to allow proper control of the power system. Therefore, communication technologies that support higher data rate as well as long distance coverage will be required. In this regards, copper-wired and fiber optic technologies not only meet both the requirements but also provide secure and reliable transfer of data. Ethernet has extensively been implemented in the current power systems for localized protection functions to provide real-time monitoring and control through local area networks [23]. While, fiber optic based communication has the potential for communication over relatively long distances without even the need for intermediate relays or amplification (see Table F.1). Communication through fiber optics is inherently immune to electromagnetic interference [23]. Dedicated cables can be used for connecting ReGen plants to the control centers with increased capacity and low latency [23]. However, the cost associated with the wired communication/networking solutions make them less attractive for long distance deployments as well as in dense urban areas, especially for the small size power plants at low voltage level. On top of a significant investment on the cable deployment, a regular maintenance cost make these approaches a weak candidate for accessing ReGen plants. Likewise, communication through the existing power lines, known as Power Line Communication (PLC) also presents several advantages. However, there are two serious issues associated with this technology that may limit their suitability in advanced distribution grid operations with increased reliability requirements i.e. **a)** periodic impulsive noise, **b)** the achieved data rate decreases with increased distance between the grid entities [23].

In such a scenario, wireless technologies, specifically cellular network based technologies (3G, 4G, LTE etc.), are considered a promising substitute to support communication between ReGen plants and the system operators. Cellular networks being mature with ubiquitous coverage enables seamless communication at relatively low cost. The advantages expected from the cellular networks that will offer advanced grid functionalities are: **a)** low installation cost, **b)** ease of deployment, and **c)** scalability etc. [23]. Further, a back communication mean will also be required to avoid loss of communication link due to unexpected failures. Although today the cellular networks have several redundant links to tackle failure situations but satellite communication can also be used to provide a redundant link, especially in remote locations.

A classification of the communication/network technologies that can support communication between ReGen plants and system operators in terms of achievable data rate and range of coverage is presented in Table F.1.

Table F.1: Comparison of Communication Technologies for Supporting Communication between ReGen and Control Center

Technology	Standard	Data Rate (Achievable)	Coverage Range
Wired Technologies			
Fiber Optics	WDN, SONET/SDH	155 Mbps - 40 Gbps	Up to 100 Km
PLC	Narrowband	10 - 500 Kbps	300 m – 1 Km
Coaxial Cable	DOCSIS	172 Mbps	Up to 28 Km
DSL	ADSL, HDSL, VDSL	1 - 100 Mbps	Up to 5 Km
Wireless Technologies			
WiMAX	802.16	Up to 75 Mbps	Up to 48 Km
Cellular	3G, 4G, LTE	Up to 300 Mbps	Up to 100 Km
Satellite	LEO	2.4 Kbps - 100 Mbps	Up to 4500 Km

F.3 Network Requirements and Challenges in Communication

Although the transmission system is physically linked with the distribution grids for power transfer between the two grid types, the actual data exchange between ReGen plants and system operators (DSO/TSO) is currently scarce when it comes to real time data. Further, distribution grid states are not monitored very effectively. With the bidirectional flow of power in connection with added ancillary services, data exchange between the grid assets is required for effective operations of the grid [6, 42]. However, when it comes to data exchange, the network is often assumed to simply work, but in fact, this component in the grid system is critical for operations to be executed as planned. If the network does not perform as expected, this may endanger the reliability of the system operation. In a machine-type communication (MTC), concerning the connectivity between any devices, there is a set of critical aspects that needs to be considered, for instance:

- Timing Requirements: how strict and how tight are deadlines for data to be exchanged?
- Reliability Requirements: how critical is it that data reaches destinations?

These two types of requirements more or less open or close different options to the type of communication that can be utilized. Generally, for any critical machine-to-machine (M2M) communication the level of reliability and availability is in the order of 99.9% magnitudes, where the severity of consequences is a matter of adding more or less 9s to the set of digits. The cost of adding more 9's however, increases heavily fast, so trade-offs and other fall back solutions must be considered as well. This in particular is an issue if the communicating entities are sharing any physical medium of communication, since cross traffic from other independent sources always has an impact on the necessary traffic.

In the following, challenges and state-of-the-art in this regards is briefly overviewed.

F.3.1 Challenges in reliable and timely communication

The Open Systems Interconnection (OSI) model divides the communication into different layers each addressing different issues in relation to communication between entities [9].

At the physical layer, the issues are focused on sharing of the communication medium (e.g. frequency spectrum, copper wire or fiber wire), i.e. how should the devices avoid interfering with each other. Different techniques are applied here, e.g. time and frequency division. Since time and frequency are constrained resources, any technology has only a limited capacity in terms of number of nodes and bandwidth at this level. Depending on the communication technology, the bandwidth and capacity may be interchangeable, i.e. with a low number of nodes, a high bandwidth can be achieved and vice versa. Physical range of communication is also a critical element, both for wired and wireless technology. Therefore, data traffic more than often is required to pass by additional network equipment such as switches, routers and so forth to cross inter-linked networks, as shown in Figure F.4. The Internet is probably the extreme case of such an inter-linked network that allows any entity to be connected (virtually) to all other nodes in the world (if the technology is implemented as intended).

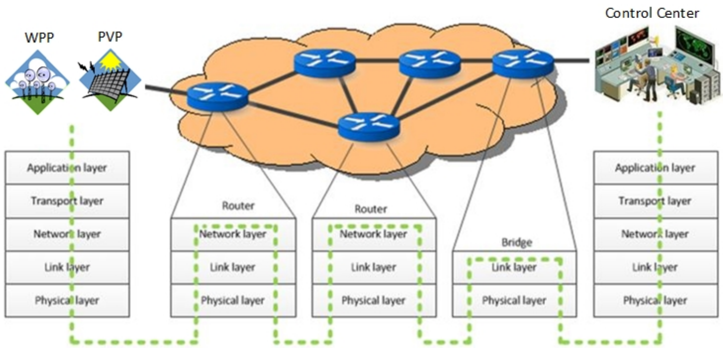

Fig. F.4: Illustration of data transport across multiple networks. Data may in public lines not travel the same route always, and be exposed to buffering due to cross traffic in the routers between source and destination.

At the nodes where traffic crosses network boundaries, data packets may be stored and forwarded – an efficient approach when the target is to support a highly scalable network of networks with thousands and thousands of nodes. However, since these nodes need to temporarily store data packets, they also need memory as a buffer. Although memory is reasonably cheap compared to the packet sizes, this store and forward mechanism becomes a trade-off between end-to-end latency and packet drops (in case buffers run out of space, incoming packets are dropped). The data is being handled by software across the communication stacks on each physical device it meets across its journey, and will be buffered at times when the device that bridges to the next link in the chain is not able to transmit. Depending on how the network is managed and whether it is a public or privately owned network, there are difficulties and levels of stochastic elements that need to be addressed to ensure timely and reliable communication.

On top of the raw data transportation between entities handled by the IP protocol, two popular transport protocols, UDP and TCP are implemented and offer different level of data transportation service quality to the application. UDP is simpler and faster due to the lack of functionality and offers the raw IP layer with some additional information; hence, transportation using UDP (or UDP like protocols) are best effort. The application must accept that packets (or data) may very well be lost in the network, e.g. dropped by a router or arrive in different order than it was send from the source.

For TCP this is different, since TCP includes mechanisms to acknowledge and retransmit data, such that data is reliably transmitted and received in causal order. However, due to retransmissions of lost data packet that are detected by timers running out, TCP generally suffers with delays when packets are dropped. This, in particular, becomes worse when networks are congested or many clients are on the same network. Although the implications of network conditions are fairly known for TCP and UDP on the delay, while its implications on the applications and in particular on networked control is not known and requires additional research. The trade-off between using TCP or UDP is in fact a trade-off between making the information loss tolerant or delay tolerant.

The reliable and timely reception of data is significantly important for a high variety of application level protocols that reside on top of the transport layer. These application layer protocols are designed to service the application and therefore come with much different functionality, which is built on the assumption of a working network. Since there are many vendors of entities, data needs to be described in a common way for interoperability of entities. Thus, protocols need to be designed such that interfaces between the sender and receiver match. It is, therefore, critical also to consider the application layer protocols when doing communication. Further, the functionality these protocols offer are disrupted by delays and packet losses, depending on the use of TCP and UDP, as mentioned earlier. Again, the use of TCP and UDP is affected by the network topology and its performance, which yet again is affected by the weakest link and physical layer in the communication chain.

Typically, most of the application layer protocols and other related standards (e.g. IEC 61850 etc.) are based on TCP because TCP being available since 1970's is well known and has been tested and widely supported. It is used as a de facto standard in industrial protocols such as MODBUS/TCP and IEC-61850 for communicating over networks [13, 26]. In the following, a brief information of relevant application layer protocols and standards (IEC based) is given that use TCP as a standard transport layer protocol.

F.3.2 Application layer level protocols

1. **Manufacturing Message Specification (MMS):** an international standard (ISO 9506) that deals with transport of supervisory control information and is a part of the IEC 61850 standard. The original implementation of the MMS was done based on the OSI model but with its own layers. However, the modern versions of this protocol use the standard TCP over IP protocol set.

2. **SOAP (Simple Object Access Protocol):** is a protocol that is used in combination with web services, and allows flexible exchange of data objects between web servers and clients. It defines message structure for expressing instances and how to process these and works on top of TCP/IP in any network types. Up to 2009, this protocol specification was maintained by the World Wide Web (www) consortium, but is continuously being used.

3. **HTTP (Hypertext Transfer Protocol):** is the classical web interaction protocol for webservers and clients, and works by a request/response pattern. Using underlying protocols between HTTP and TCP, security can be obtained via e.g. the TLS protocol that encrypts the HTTP session when being exchanged via TCP. HTTP is developed and maintained by the IETF and W3C.

F.3.3 IEC based Standards

The International Electrotechnical Commission (IEC) has proposed a number of standards on the communication and control of electric power systems. In the following, a brief overview of relevant IEC based standards is provided:

1. **IEC 61850:** The standard 61850 [4] focuses on the substation automated control. It defines comprehensive system management functions and communication requirements to facilitate substation management. The management perspectives include the system availability, reliability, maintainability, security, integrity and general environmental conditions. IEC 61850 series consists of ten parts (all parts may have not been published yet) and is a part of the working group TC57 reference architecture. In particular the parts IEC61850-7 and -8 are of interest to the communication, also the IEC-61850-90-1 and -2 are of interest. The abstracted models of communication can be mapped into a number of already existing protocols, e.g. MMS and web services [4]. The protocols run over TCP/IP over public as well as private networks to ensure response times for certain services. The standard includes data modelling, reporting schemes, fast transfer of events, sampled data transfer, commands, storage and other relevant issues for the project.

2. **IEC 61400:** The IEC 61400 [3] standard defines all relevant parts for installing and using wind turbines. For the communication aspect the 61400-25 is the most interesting part since this focuses on monitoring and control of wind power plants. In this part, overall description of principles and models are described, information models and exchange mechanisms are described as well as a mapping to communication profiles are described. This includes details on the use of existing protocols such as: SOAP/web based services, MMS, OPC XML and DNP3 (Distributed Network Protocol 3) etc.

3. **IEC 60870 [2]:** defines systems used for tele-control (supervisory control and data acquisition) in electrical engineering and power system automation. Such systems are used for controlling electric power grids and other geographically widespread control systems. By using the standardized protocols, equipment from many different suppliers can interoperate. IEC 60870 consists of six parts that define general information related to the standard, operating conditions, electrical interfaces, performance requirements, and data transmission protocols. Part 6, defines the Inter Control Center Protocol (ICCP) and uses a client/server approach with the control centers as being either client or servers (they can be both). According to [7], TCP over IP is a common approach of implementation over any type of transmission media.

F.4 Delay Tolerant Vs. Loss Tolerant Information

Time is critical for many applications, especially for delay-critical grid applications (e.g. protection and control related) where real-time transmission of data is required [25]. According to [25], a communication channel latency for the transfer trip protection of a distribution system is between 8-–16 ms. While, one of the problems with TCP [32] is that, in case of a packet loss, the application cannot access the next packets until the retransmitted copy of the lost packet is received (due to ordered data transfer). Further, in case a TCP connection is lost/terminated due to poor network conditions, TCP uses three-way handshake to re-establish a connection – that too at the cost of time. The three-way handshake required to establish a connection is also repeated every time if the TCP session is closed each time after sending the data. However, keeping a channel open/established requires additional network and computational resources. Therefore, generally where TCP is unsuitable, its counterpart UDP is used.

Yet the effect of packet loss and delays in the reception of critical information vary from application to application. Reference [32] and [39] present the impact of increased packet loss rate and latency using both transport protocols (TCP and UDP). The analysis in both research papers is based on the concept that the information element used at the receiver does not match the current true value at the remote location. This concept is termed as mismatch probability (*mmPr*), see [11]. In the context of *mmPr*, two entities A and B are considered. Entity A (receiver) is obtaining the information element from B over a network which may have stochastic end-to-end delays and message loss occurring due to packet losses at the network layer. The information on B is dynamically changing, hence during transfer from B to A, the information at B may have changed its value resulting in information at B and A are not matching. In general, a low mismatch probability is desired as in most cases, applications benefit from using correct information. Therefore, the mmPr can be and has been used to locate trade-offs between various parameter as update time intervals [27] or caching times [31]. However, in recent study the trade-off using this metric, between TCP and UDP or more generally, the trade-off between adding delay for retransmission versus allowing packet losses was analyzed in [32].

The results shown in Figure F.5 illustrate the values where TCP and UDP for the given packet loss/delay leads to the same mismatch probability, thereby showing the trade-off between packet loss probability and mean delay it takes to achieve same level of mismatch probability for a proactive, periodic update approach. For a message lost because of packet loss, using UDP leads to an effective reduction of update rate, which increases the mmPr. If for the same packet loss occurs using TCP, the retransmission scheme leads to retransmissions of the packet(s) effectively keeping the update rate, however at the cost of an extended delay caused by the retransmission scheme. Hence, the plots in Figure F.5 show the mean delay that a TCP based protocol should attain if the same mmPr as a UDP based protocol should be achieved. For example: given an event rate of information of one event per 10 seconds ($\lambda = 0.1 event/sec.$), and a packet loss probability of 0.5%, a TCP connection (or any retransmission based scheme) could spend up to 6.12 seconds to transmit data correctly before it would become better to use a UDP based protocol and accept message losses. If the event process changed to, for instance, 1 event per second in average ($\lambda = 1 event/sec.$), this delay boundary becomes even lower for TCP, and spending more than 0.922 seconds in average when using a retransmission based scheme (e.g. TCP) it would be better to accept packet losses and use, for example, UDP. Notice that the results here also depends on the time interval between updates, so Figure F.5 will change if another update rate is chosen.

Comparing these results with those in [32], TCP is in general performing poorly in the situation of sending dynamic data over network. However, as Figure F.5 indicates, there is room for adjusting e.g. timeout values to accommodate for the losses for slow dynamic information ($\lambda = 0.1 events/sec$), where a significant amount of time can be spent on retransmission before

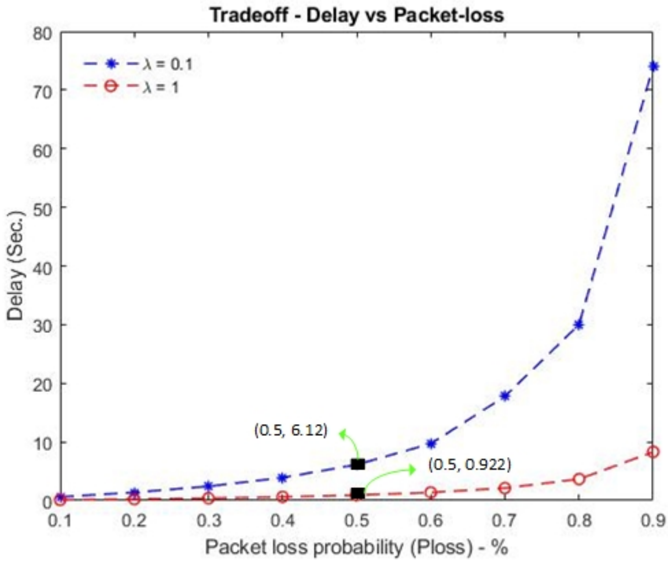

Fig. F.5: Trade-off lines between packet-loss and end-to-end delay for a given propagation delay at two different event rates (assuming exponential random process with rate λ, and independent packet losses). Lines show where UDP performs exactly as good as TCP.

it no longer pays off. For faster information dynamics (here, 1 *event*/*sec* in average) there is so little time in overhead that it is very unlikely to be possible. Thus, one of the direct solutions is to modify TCP as required, as for instance, almost all high speed TCP variants fall into this category. However, modifying TCP is not easy in practice [15]. It is very hard in closed source operating systems (e.g. Windows). Even in open source operating systems (e.g. Linux) it will require recompilation of the kernel. Therefore, another solution is to modify UDP by adding reliability and other highly related/relevant properties (as adjusting the timeout value etc.). In this regards, UDT–UDP based Data Transfer protocol [15, 16] is an example where UDP has been modified for distributed data intensive applications over wide area high-speed networks.

Based on the complexities associated to the transport layer protocols (and several other reasons); the concept of GOOSE (Generic Object Oriented Substation Events) message was introduced. GOOSE is a part of the IEC 61850 standard and is used for fast real time transmission of data within a substation network [24]. It embeds some of the OSI layers i.e. based on VLAN and Ethernet technology, but bypasses the transport layer to avoid all its complexities. However, in order to get a fast real time transmission of data outside the substation network, Routable-GOOSE (R-GOOSE) is an emerging solution to improve power system protection, control, and monitoring [24], where R-GOOSE messages are routed over UDP/IP headers [24]. This in fact opens several questions and directions for future research in smart grid communications i.e.

- Is TCP always the most suitable transport layer protocol, especially in case of fast and real time data transportation in smart grids?
- What would be the impact of delayed or lost information on a specific application over a TCP based network?
- Communication standards (e.g. IEC based) and other related application layer protocols are typically based on TCP. Should these always be on top of TCP?
- Is there really a need to design/implement a new transport layer protocol on top of UDP?
- What needs to be changed at the application level layer if GOOSE or other such messages are based on UDP/IP?

F.5 Challenges in Secure Communication

In addition to the reliable and timely communication, the security of power systems from cyberattacks is critically important. The authors in [33] have analyzed the impact of cyberattacks on on-line voltage control coordination from ReGen plants and have also highlighted its consequences in terms of the power losses. Appropriate cyber-security solutions not only for each GSS but also for the entire smart grids are required. In case of ReGen plants communicating with the control centers, the system should ensure authorized access to the data and control functions to/from the communicating entities and that resilient encryption algorithms are used to prevent spoofing of sensitive data. IEC has also defined a standard for the security of its protocols in IEC 62351 [5]. This standard specifies the requirements to achieve different security objectives such as data authentication and confidentiality, access control as well as intrusion detection.

F.6 Conclusion and Recommendation

The bulk integration of renewable energy in the current power system will lead to fundamental changes in the way transmission and distribution network operators will have to manage the voltage and frequency stability in the future power systems. To make sure that the bulk addition of wind and solar PV is not detrimental to the overall stability of the power system, these ReGen plants will have to play a role not only into the energy production, as it is today, but also into the delivery of system services which are needed to ensure the system stability comprising both transmission and distribution level. The underlying communication network infrastructure will be an essential component in the new renewable energy rich power system for effective system control. This paper characterizes and presents the control and communication network architectures, performance requirements and research challenges for integrating ReGen plants in the current power grid. It has been ascertained that reliable and timely communication are the most critical requirements in such a scenario, which is influenced by the underlying transport protocols in the protocol stack. Similarly, network security is also a challenging problem for the communication network that will be used to control power systems. This paper summarizes the current research status on control and communication network architecture in the next generation power systems with huge penetration of renewables by putting forth some questions and directions for future research. A lot of research effort is still necessary before the communication infrastructure can be employed for future resilient and smart energy system.

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Paper G

Information Reliability in Smart Grid Scenario over Imperfect Communication Networks using IEC-61850 MMS

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Abstract

The trend of producing energy from Renewable Generation (ReGen) plants is greatly increasing. This leads to the objective of building future power generation system entirely based on renewable sources. Since the power output of ReGen plants, such as wind power plants (WPP), varies continuously and thereby the voltages in the distribution grid, an effective control system is required, to govern the production from all ReGen plants. For this, control messages must be exchanged between the grid assets with reliable information to achieve optimum efficiency. This raises a challenge to assess information reliability and evaluate the performance of a controller. Therefore, considering the dynamic nature of information, this paper analyzes the information reliability in terms of correct and timely delivery of message signals, for remote control of a WPP using IEC-61850 MMS in a smart grid scenario. Based on this measure, the quality of controller performance is also calculated over various imperfect network conditions.

G.1 Introduction

Power generation in past was mainly based on big centralized power stations such as nuclear power plant, fossil fuel, gas, coal fired and hydroelectric dams. However, with advancements in technology and the aim of protecting the environment, Distributed Energy Resources (DER) based on Renewable Generation (ReGen) plants are taking over worldwide, especially in Europe, Canada, USA and Japan [12]. For instance, with the addition of ReGen plants into the power grid, Danish parliament aims a 50% reduction of fossil fuels for the production of electricity and heat by 2020 [9], while a 100% renewable energy based power system by the end of 2050. DER is different from centralized power generation in that it is distributed and easy to install. It produces electricity in an environmental friendly, secure, sustainable and reliable manner. However, the biggest challenge of a DER network is to monitor and control its operations. For control and management of DER, the concept of microgrid was introduced. Microgrid is a small scale power system comprising of DER, Distributed Energy Storage (DES) and controllable loads. The purpose of a microgrid is to self-maintain DER in conjunction with transmission, distribution and storage of electricity. It also seamlessly has a synchronized connection to a utility power, and can also operate as an independent power system [11].

In order to realize the objectives of DER, microgrid requires a control system to actively balance between energy production and consumption. The microgrid control system has a hierarchical control structure consisting of a medium voltage grid controller (MVGC), and a low voltage grid controller (LVGC) employed for controlling the medium voltage (MV) grid and low voltage (LV) grid respectively [2]. The major requirement of a microgrid is an interconnection of its components to a control-center via a communication infrastructure, to support a variety of messages, such as real time monitoring, control, demand and response. All such communication messages have their own transfer time and reliability requirements, which must be satisfied for a reliable operation. Therefore, analysis of network performance, in terms of reliability, is of critical importance in a DER network.

The transport layer protocol, TCP guarantees a reliable exchange of information between the two end devices, but at the cost of higher end-to-end delays (depending on the network conditions). Since TCP was not designed considering the requirements of data for smart grids, the reliability it offers may not be beneficial for many of its applications where timely reception/transmission of data is much more important than 'delivery at any cost'. Therefore, it is highly important to analyze as to which transport layer protocol (TCP or UDP) provides higher reliability in terms of timely delivery of information. In this paper, the timely delivery of information is determined by measuring the level of match of information between sender and receiver. The reason for this measure is that a mismatch of information between the ReGen plant and the controller, may potentially lead to the degradation of the control performance, affecting the overall stability of the power system. Based on the same measure, the quality of controller performance has also been measured under different network conditions.

Several standards have been proposed related to the communication aspects in electric power systems, especially microgrid. Since IEC-61850 is becoming the de-facto for the communication between DER and control center, it has been implemented in this paper. IEC-61850 series consist of ten parts, and is a part of the working group TC57 reference architecture [1]. It addresses the major concern of interoperability issue of IEDs/devices at bay level –a physical device connected to the network in a substation. The abstracted models of communication can be mapped into a number of already existing protocols, e.g. MMS, GOOSE, and soon the web services as well. The protocols may run over TCP/IP protocol stack, based on public as well as private networks, to ensure response times for certain services. The standard includes data modelling, reporting schemes, fast transfer of events, sampled data transfer, commands, storage and other relevant issues for this work.

On top of IEC-61850, we use Manufacturing Message Specification (MMS), which is an application layer protocol that defines rules, syntax, objects, structure of messages, and services to control, monitor, supervise devices [7]. It is an internationally accepted and widely adopted standard protocol, by industrial and manufacturing organizations that address interoperability issues of different vendor devices into smart grid. It thus provides benefits of flexibility of choosing devices from different manufacturers, reduced cost, product innovation, independency and interoperability [7] [10]. It is not concerned with how messages are traversed over the network and defines a local language translator, referred to as Virtual Manufacturing Device (VMD). VMD plays the role of a language translator which ensures correct understanding and delivery of messages among devices [7] [10].

MMS architecture follows a client-server model. Real industrial devices such as Integrated Electronic Devices (IEDs) act as MMS server, allowing MMS client to control, supervise and access the information from them. Therefore, ReGen plants, for instance wind power plants (WPP), have an IEC-61850 server (also called IED) that is controlled and monitored by a controller having an IEC-61850 client. Here, MMS client can be an application, HMI or SCADA machine at the control center. The IED represents all parameters of ReGen plants that are readable and/or writeable by the client.

There are a number of challenges in controlling RES by remote controller (MVGC) such as latency, quality of service, scalability, reliability and security [6]. But this research focuses on network challenges, which are related to transportation of control messages over a communication network, such as latency, reliability, packet losses, network unavailability. The remainder of this paper is organized as follows: Section G.2 provides the related work and brief introduction of the quality metric to be used. Section G.3 presents the scenario of the system adopted in this paper. Section G.4 is related to the requirements of IEC 61850 MMS, and challenges of integrating it to support remote control communication for DER. It also covers the modeling and design of WPP production levels. Section G.5 provides the details of parameters used, and the implementation of IEC-61850 MMS model. It also explains the network topology and different parameters used in this paper. While Section G.6 and Section G.7 finally present the conclusion, recommendations and suggestions for future work.

G.2 Related Work

In this paper, the quality metric used to measure communication reliability, is based on the notion of the mismatch probability (mmPr) [5]. It is the probability that a certain information for processing by the controller does not match the value at a sensor in ReGen plant [4], defined in (G.1):

$$mmPr = Pr(I_{cc}(t_c) \neq I_{ct}(t_c)) \tag{G.1}$$

Here, I_{CC} and I_{CT} is the information available at the control-center and the controller respectively, while t_C is the control time where the two sets of information are compared. mmPr is not only recognized as a plausible quality metric for managing the dynamic subscriptions in the context management systems [4] [8], but is also used in the smart grid domain for finding an optimal waiting time of arriving at the DER, as well as their assignments to the aggregator control units [8] to control a set of DERs. This quality metric considers the network delay, information dynamics as well as the information access strategy in one single metric. Therefore, it makes it simple to analyze one single scaler value instead of several distributions in combination, for example, long delays and long event intervals compared with shorter delays and short event intervals versus update rates etc. Out of the three information access strategies (i.e. reactive access, proactive-periodic and proactive event-driven access) mentioned in [8], the reactive strategy (based on request-response strategy), is implemented in this work, because as mentioned in Section G.1, IEC-61850 MMS architecture follows a client-server model which is based on the request-response strategy.

G.3 Scenario Description

Figure G.1 presents a microgrid scenario that comprises of a MV distribution system with three PVP plants (PVP1, PVP2, PVP3) and a WPP. A MV grid controller (MVGC), shown in Figure G.1, is responsible for ensuring that all control objectives are met. This MVGC, (could be a hardware control unit), can be placed locally in a primary substation or at the DSO control center. The scope of this research is to focus the communication between a single WPP and MVGC, as shown in Figure G.2. Thus, in order to implement demand-supply balance, the MVGC requires information about current energy production from WPP, and consequently direct it for any increase/decrease in the production. For this, MVGC periodically requests for the current state of energy production from WPP, which responds back accordingly. This is also known as a client-server communication model, as shown in Figure G.2, where MVGC being a client (requester), and WPP is a server. Since the objective of MVGC is to meet energy balancing goals, based on collected data, it takes control decision of increasing/decreasing power production level, by increasing the transition rate of state by some value (later referred to as Δ), so that it can push WPP in a desirable state of power production.

G.4 Information Modelling

Having described the scenario adopted in this paper, it is now necessary to model the required states of information of the current energy production generated by a ReGen plant. Since energy produced by WPP is a stochastic process, and can have multiple levels of production with time, Markov chain is one of the most commonly used tools for modeling such stochastic processes. Thus, it is assumed that a process of power production has finite number of states, S_1 to S_M, as shown in Figure G.3. These states represent the amount of power generated by the WPP, for instance, state S_1 represents the

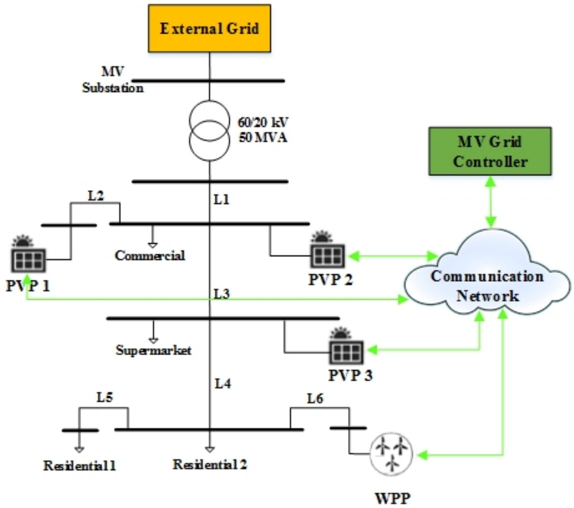

Fig. G.1: Microgrid Scenario

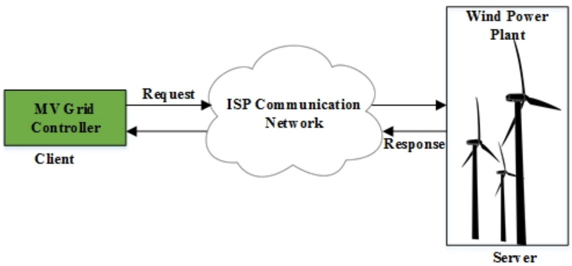

Fig. G.2: Client-Server Communication in Microgrid

power generated from 0 to 1 kW, state S_2 represents power generated from 1 to 2 kW, and so on. If WPP is in state 1, it jumps to state 2 with a transition rate of λ, and back from state 2 to 1 with a rate μ. This applies for all states, as shown in Figure G.3.

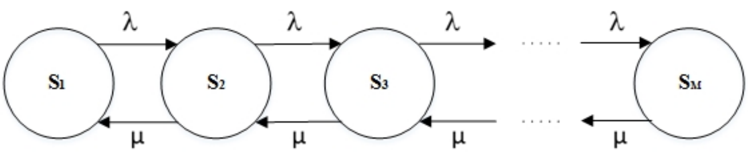

Fig. G.3: Markov-chain model of wind turbine energy production

The WPP is designed to send status updates periodicaly to the MVGC through the communication network. In this model we do not consider the mechanical dynamics of the wind turbines, since events at instant speed lead to a change in production. However, due to the physical properties of a wind turbine this is not the case, as there will be some delay between the wind change and the change in output. Therefore, this model is better suited for PVPs though.

IEC-61850 MMS Modelling

IEC-61850 MMS was originally designed for OSI networking model, but since TCP/IP was never replaced by OSI [3], MMS is eventually mapped over the TCP/IP. For this, an interconnecting layer is used between TCP/IP T-profile and OSI A-profile layers [3]. This paper also models MMS over TCP/IP. Figure G.4 represents the protocol layers of MMS over TCP and UDP.

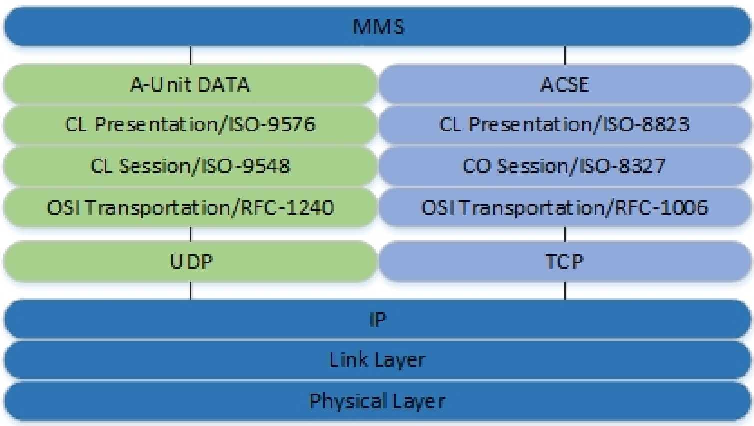

Fig. G.4: The protocol layers of MMS over TCP and UDP [3]

Before sending MMS request by a client, it should establish an MMS association with MMS server. Further, it should establish a connection on the transport layer. In case of connectionless-mode, it does not require handshake at transport layer, and should make connectionless MMS association that simultaneously establishes and releases an association. Since the main focus of this paper is to analyze the impact of network delay, and packet losses on quality of MVGC performance and reliability of MMS server information, it has therefore been assumed that initial handshake in both layers (OSI and MMS) is already established. The area of study only focuses on main MMS request and response operation between MMS server and client.

MMS Server Modelling

As mentioned above, the process of power production of a WPP is modelled using a Markov birth/death chain, with the states representing the level of power generated by WPP. The Markov chain is mathematically described by the generator matrix Q with M finite states of the power generation, as in (G.2):

$$Q = \begin{bmatrix} -\lambda_{12} & \lambda_{12} & 0 & \cdots & 0 \\ \lambda_{21} & -(\lambda_{21}+\lambda_{23}) & \lambda_{23} & 0 & \vdots \\ 0 & \lambda_{32} & -(\lambda_{32}+\lambda_{34}) & \lambda_{34} & \vdots \\ \vdots & \vdots & \ddots & \ddots & \vdots \\ 0 & 0 & \cdots & \lambda_{M(M-1)} & -\lambda_{M(M-1)} \end{bmatrix} \tag{G.2}$$

Further, assuming that the system is at state i, the transition probability that the next state transition will be state j, calculated by (G.3), as:

$$P_{ij} = \frac{\lambda_{ij}}{\lambda_{ij} + \mu_{i_{i-1}}} \tag{G.3}$$

Practically, the MVGC (client) should have the ability to interrupt any state of WPP (server), so that the server can follow the controller's instruction immediately. However, in order to simplify our model, it is assumed that the system remains in each state, until its Mean Holding Time (MHT) expires. The MHT is defined as the time spent by system in a state, calculated in (G.4), as:

$$MHT = \frac{1}{\lambda + \mu} \tag{G.4}$$

At the beginning, (t = 0), the initial probability is P_o = [1, 0, 0, 0, 0, 0]. It is the probability that system is in state S_1 at t = 0 and remains in the same state until its MHT expires. The WPP then jumps to state S_2 and remains in the same state until the MHT expires. It keeps on jumping to different states, back or forth, decided by a random number generator. If the random number is greater than the probability of moving forward, the system jumps forward, if not, it jummps to the previous state.

MMS Client Modelling

MVGC acts as an MMS client and it is responsible of controlling the power production of WPP. Thus, it has been designed such that it speeds up/down the process of power production, to keep the output power level in the desired state/s. Here, it is assumed that states S_3 and S_4 are the desired states. Now, in order to represent the control actions carried out by MVGC, to get to the desired state under the influence of some random events, we use Δ to simplify our model. For instance, if WPP is in a state below S_3, the MVGC sends a control signal to increase the transition rate with a value of Δ, as shown in Figure G.5(a). Similarly, if WPP is in any state above S_4, it increases the transition rate in backward direction with same value of Δ, as shown in Figure G.5(b).

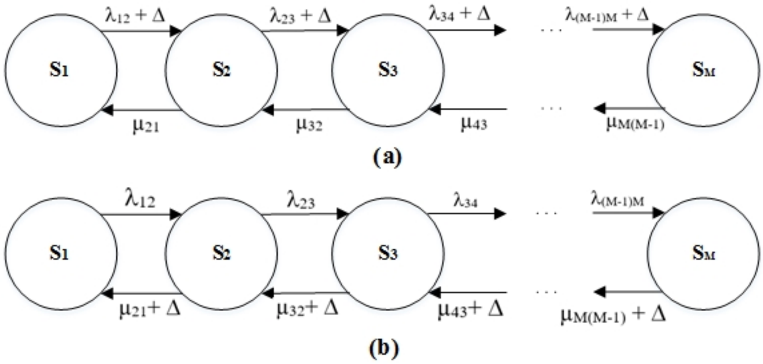

Fig. G.5: State transition diagram with (a) rate $\lambda + \Delta$ in forward direction (b) rate $\mu + \Delta$ in backward direction

Defining the Quality of Controller

One of the objectives of this paper, is to evaluate the quality of the controller performance for different network conditions. Since the function of controller is to keep WPP in a desirable state, the quality of the controller performance is measured using (G.5), as:

$$QoC = \frac{\pi_i}{T_{total}} \tag{G.5}$$

Here, QoC is the quality of the controller performance, π_i is the steady state probability of being in state i, and T_{total} is the total time used to observe the system. It has been assumed that the desirable states of the server are S_3 and S_4, therefore QoC is given by (G.6) as:

$$QoC = \frac{\pi_3}{T_{total}} + \frac{\pi_4}{T_{total}} \tag{G.6}$$

Here, π_3 and π_4 denote the steady state probability of being in state S_3 and S_4, respectively.

G.5 Network Parameters and Topology

The performance assessment cases are classified into three groups based on the network performance parameters of packet delays, transport layer connection lost, and packet losses as follows:

Case 1: Network Delay: Assess mmPr and controller performance of MMS model over TCP and UDP for different packet delays

Case 2: Network Unavailability: Assess mmPr and controller performance of MMS model over TCP and UDP in case of network unavailability

Case 3: Network Link Error: Assess mmPr and controller performance of MMS model over TCP and UDP for packet losses

MMS traffic was generated over TCP and UDP as an underlying protocol, using NS3 as a network simulation tool. The traffic was sent between MVGC and WPP, and all test cases were executed for different network conditions. The tests were performed by generating 10,000 MMS requests both for TCP and UDP, with a request rate of 1 packet per second (i.e. a total of 10,000 sec.). The trace files collected for both transport layer protocols were then analyzed using MATLAB, in order to understand the impact of network performance parameters, i.e. data reliability in terms of mmPr, quality of controller performance and performance of MMS communication over TCP and UDP.

Simulation Parameters

The scenario and MMS server-client model considered for this paper has several parameters. Different values of these parameters can lead to multiple test cases and diversity in the research work. To be left as future work, values of different parameters are assumed to be constant. Table G.1 lists the parameters and their respective values considered in this paper.

State transition rate in forward and backward directions are represented by λ and μ, respectively. Here, λ and μ are exponentially distributed random variables with a mean value of 1. The mean value of exponentially distributed random variables represents the mean waiting time to enter into another state. It has been selected to be 1, so that the state of WPP can be analyzed every second. Moreover, for the purpose of modeling WPP energy production as a continuous Markov random process, all the values of λ and μ are kept different, to model the fluctuations and variations in wind speed. Upon intervention of the controller, the state transition rate will drift up with constant rate of Δ. Here, Δ is used to increase the transition rate, so that WPP (server) can reach the desirable state rapidly. To find an optimum value of Δ

Table G.1: List of Parameters and their values

Parameter	Description	Value
λ	Sate transition rate in forward direction	λ_{12}= 0.63, λ_{23}= 0.3, λ_{34}= 0.02, λ_{45}= 0.01, λ_{56}= 0.91
μ	State transition rate in backward direction	μ_{65}= 0.21, μ_{54}= 0.36, μ_{43}= 0.11, μ_{32}= 0.97, μ_{21}= 0.43
Request Rate	MMS client request rate to query about server state	1
Δ	Drift rate to increase state transition rate in forward/backward direction	0.5
Desirable State	Desirable state from controller perspective	3 and 4

is an additional research problem. It could be kept varying between 0 to 1, in order to find its optimal value for our model. However, for this paper a mid-point value of 0.5 has been selected.

Network Topology

IEC-61850 supports flexibility of choosing different communication networks for example 3G, 4G, LTE and WiMAX etc. However, the goal in this work is to evaluate the network performance using IEC-61850 MMS remote control communication. In order to achieve this goal, an Ethernet based Internet Service Provider (ISP) cloud has been used as a communication medium, with a channel bandwidth of 10 Mbps for MMS communication between MVGC and WPP. For now, it has been assumed to be a non-shared medium.

G.6 Results and Discussion

Case 1: Network Delay

Packet delays of different values were used in this case, so that the results can be mapped on network delays (latency) of different communication technologies (e.g. DSL, LTE and WiMAX). With different delay values, 10,000 MMS request packets were sent from the MMS client to the MMS server through the communication medium, with 0% packet losses for a period 10,000 seconds. This means, an MMS request is sent from client to server every second, to perform control action based on received information.

Figure G.6 shows the assessment of mmPr for MMS model over TCP and UDP based on network delays as well as the quality of controller performance for the same case. It has been observed from Figure G.6 that, for communication over TCP and UDP, the mmPr increases with latency. The reason for this is that when the response message arrives with higher delay, there are higher chances that the current state of server may have jumped to the next state, causing a mismatch of information. On the other hand, it can also be seen that the impact of latency on data reliability remains the same for MMS over TCP and UDP. This is quite an expected result, because under normal conditions of network, TCP and UDP show the same performance. TCP only differs in that it requires two 3-way handshakes, i.e. one on the transport layer, and another on application layer for MMS, before starting MMS data exchange [6].

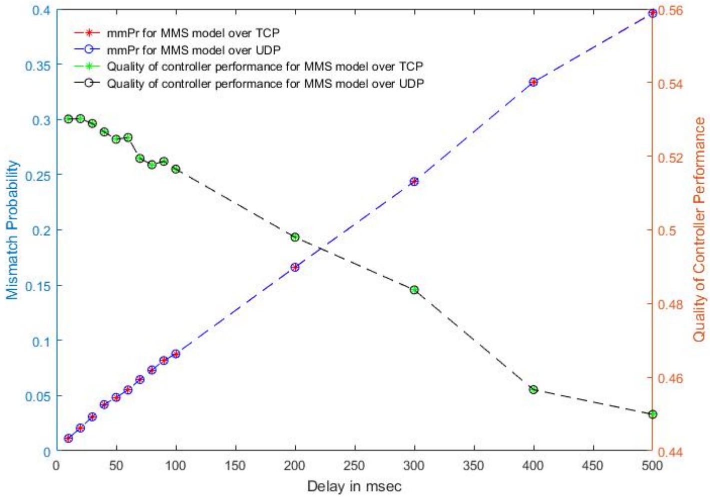

Fig. G.6: Assessment of mmPr for different network delays

Before discussing the results of quality of controller performance, it is necessary to mention that this performance has been calculated using (6), defined in Section G.4. However, it cannot be analyzed independently, because it highly depends upon the amount of time the server (WPP) spends in the desirable states. As described in Section G.4, the server remains in each state until its MHT expires, even in the absence of controller. Therefore, it is necessary to calculate the percentage of time, during which the server stays in state

S_3 and S_4, when there is no control from MMS client (controller). Considering up to 10 states of the server, it has been recorded that around 30% to 40% of the total time server remains in states S_3 and S_4. Based on this baseline for the controller performance, it can be observed from Figure G.6 that the controller performance is 53% in start. However, the delay in response may lead to mismatch of information, leading to wrong control actions. Thus, the controller quality degrades to 45% approximately. Furthermore, test results show that behavior of the controller performance remains the same for TCP and UDP, because of their same behavior.

Case 2: Network unavailability

This case was carried out to evaluate the impact of network unavailability which, causes a connection lost at the transport layer. Different connection lost time durations were used to analyze the results. However, a connection loss for only 10 seconds time duration is shown here. Additionally, connection is lost after every 2000 seconds, thus, the number of connections lost, is counted to be 5 in a total time of 10,000 seconds. As in case 1, this case was also performed with different latencies, using 0% packet losses, so that the test results can be compared with the results of case 1. The results in Figure G.7 show that there is no such impact of connection lost for 10 seconds duration on mmPr, even for TCP, because 10 seconds of connection lost is considered as if the controller was absent for 10 seconds. In case of no controller, there is no request from controller, and ultimately no chance of mismatch of information.

It can be observed from Figure G.8 that the controller performance is not effected much by such a short duration of network unavailability of 10 seconds, compared to the total duration of 10,000 seconds. Thus, as soon as the network becomes available, the controller starts working normally. However, the assumption that the controller cannot interrupt the server, if it jumps into a new state until its MHT, has a major impact on controller-s performance. This however, can be improved if the controller is given full charge of interrupting the WPP-s states at any time. Furthermore, the controller performance for TCP and UDP is observed to be the same for different network delays with no packet losses.

Test Case 3: Network Link Error

In order to evaluate the impact of packet loss on the MMS model, a range of network error rates were introduced in the network, ranging from 0.001 to 0.05. The idea is to understand the behavior of the MMS model running over UDP and TCP. The loss of packets with UDP would cause a loss of a client request, or loss of server response. Whereas for TCP, the communication

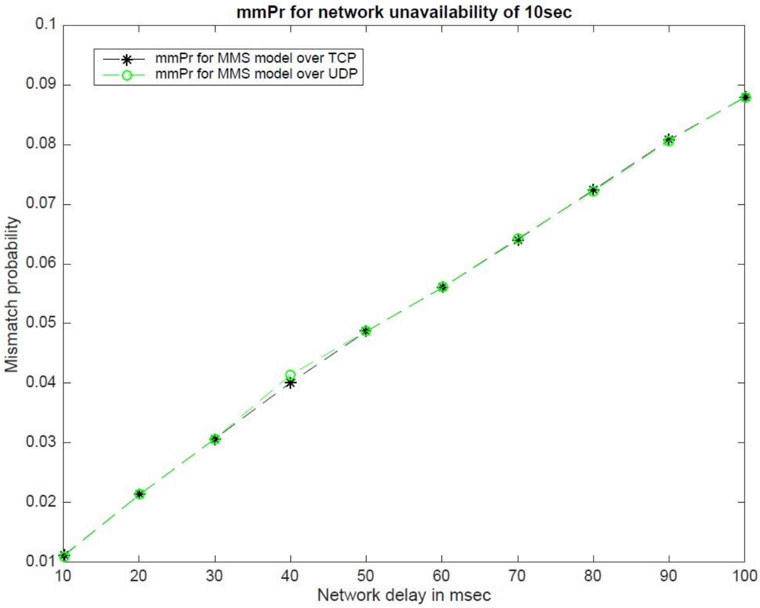

Fig. G.7: mmPr with network unavailability of 10 Sec. for 5 times

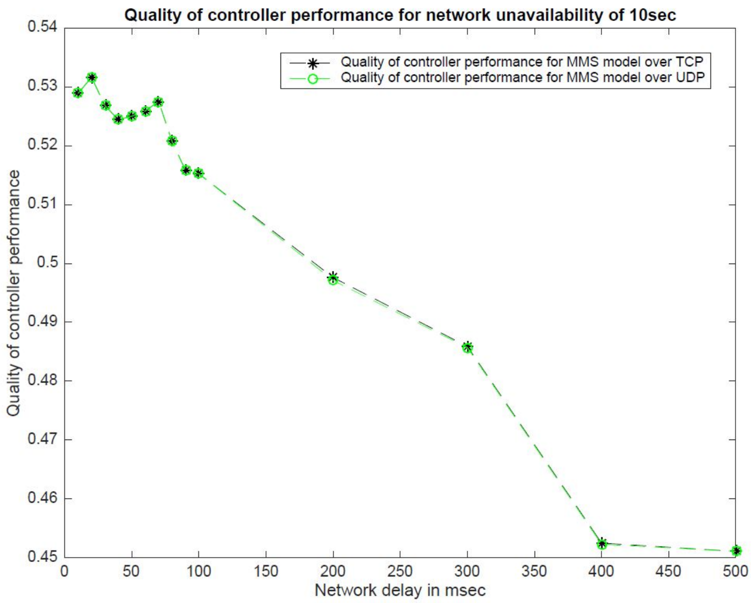

Fig. G.8: Quality of controller performance with 5 TCP connection losses for 10 Sec.

is connection-oriented, where a lost packet is retransmitted. Presumably, it can be ascertained that the more errors, the higher the packet losses will be, effecting the mismatch probability and ultimately the controller performance. This however, is tested using the IEC-61850 MMS model designed in this paper.

Figure G.9 shows that increase in packet losses causes increase in mmPr both for UDP and TCP. In case of TCP, each time a packet is lost, it is retransmitted causing delay in the request/response packet. The retransmitted response packet carrying the information from the server, may become outdated for the controller, causing mismatch of server state information. However, in case of UDP, packet losses have no significant impact on mmPr. If any request/response packet is lost during transmission, the next request message can recompense the job of getting latest information, as observed in Figure G.10 . It is also important to note that, percentage of packet losses is higher for TCP than UDP, simply because TCP has a larger number of packets for request/responses, due to the acknowledgement mechanism.

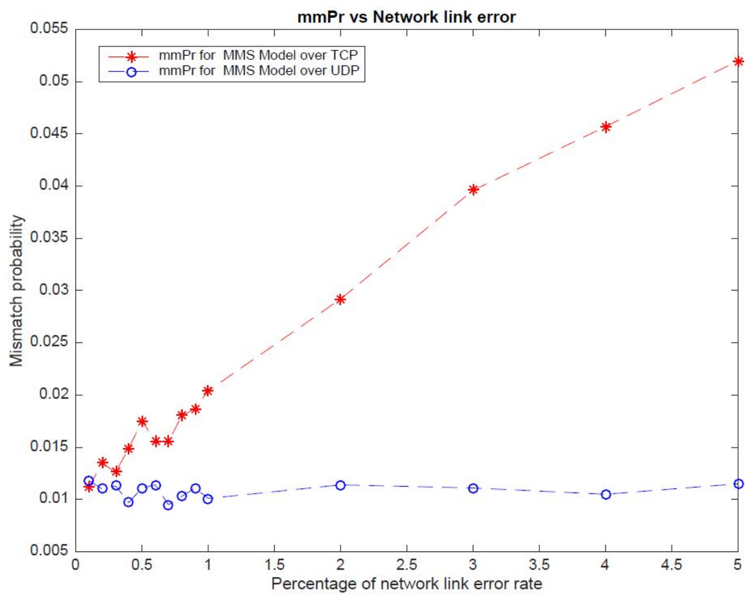

Fig. G.9: mmPr for different network link errors

For the quality of controller performance, in case of TCP, it can be observed from Figure G.10 that there is a trade-off between packet losses and performance of controller. As packets are lost in the network, the controller is not able to make timely control actions, degrading the controller's performance quality, as shown in Figure G.10.

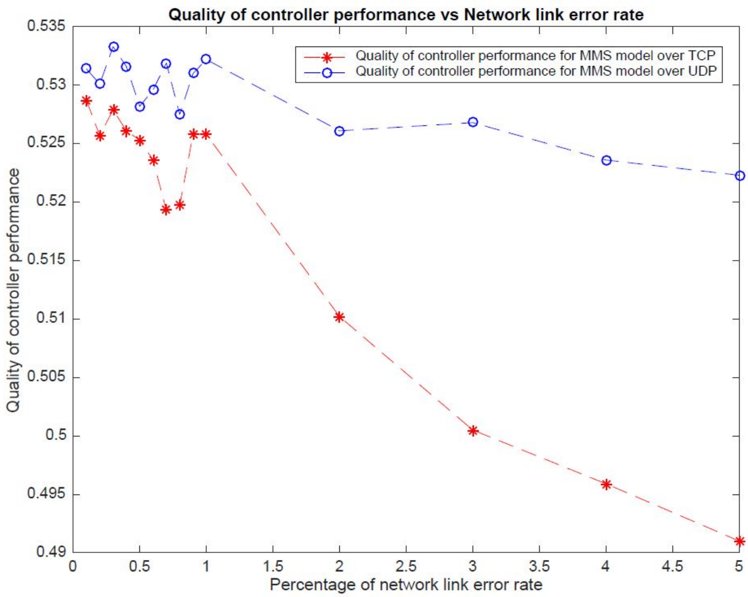

Fig. G.10: Quality of controller performance for different link errors

G.7 Conclusion And Future Work

In this paper, a simulation based model for IEC-61850 MMS has been established, in order to provide an experimental study for assessing reliable power balancing in the MV microgrid, over different communication technologies, to compensate imbalance between demand and response. This research work introduces a way to measure quality of controller performance, in the interest of balancing energy generation and consumption. One of the focal point in this paper is to understand the behavior of mmPr with the injection of MMS traffic over TCP and UDP across simulated ISP network cloud. ISP cloud provided with different network delays, has significant impact on mmPr, which enables to conclude that increase in network delay increases the mmPr.

The results revealed that under normal conditions with zero packet loss and network unavailability conditions, mmPr for MMS model over TCP and UDP gives almost the same results. The slight difference is noticed because TCP requires additional steps of transport layer and MMS association handshakes in comparison to UDP. Theoretically, there s always a tradeoff between quality of controller performance and mmPr, network delay and unavailability, which can be observed from the results. However, the quality of controller performance is also dependent upon the design of a particular controller. It was also observed that packet loss has heavy impact on MMS model for TCP as compare to UDP. mmPr for TCP is higher than UDP mmPr. On the other hand, retransmission of lost packets in TCP brings no good for controller performance. While, in UDP, packet loss has not affected the controller performance much with a request rate of 1 second. However, if the request rate is reduced, controller performance may also have effected in case of UDP. For the designed IEC-61850 MMS model, TCP and UDP have no dominance over each other under different network delays. While in case of network unavailability, each time the network is restored, TCP requires extra steps for handshaking in comparison to UDP. However, with increasing packet rates, our studies indicate that UDP performs better than TCP.

There are several simulation parameters involved in this work, as mentioned in Section G.4, which can be varied to make the system more realistic, near to real scenario. The model designed for energy production from WPP can be extended in different ways, for instance, incorporate the ON/OFF state of wind turbine along with finite/infinite states of energy production levels. Similarly, the MVGC s function can be extended to be more interactive by taking the input from relevant stakeholders who take care of energy demand and supply. In future, more test cases will be executed to analyze the use of TCP/UDP in a smart grid scenario based on mmPr and controller quality as a function of varying request rate, as well as a function of varying cross traffic. Finally, the performance of TCP and UDP based on mmPr will be analyzed on specific communication technologies e.g. WiMAX, LTE and WiFi etc. in an HIL environment.

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